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**THEORETICAL and TECHNOLOGICAL
FOUNDATIONS of GENTLE GRAIN
LOADING INTO SILOS**

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The monograph comprehensively examines the process of gentle loading of grain into silos and the factors affecting grain quality during transportation, handling, and storage. It considers the physical and mechanical properties of bulk grain materials, the causes and types of mechanical damage to grain, and the structural features of grain storage facilities, particularly metal silos. The monograph investigates mathematical models of grain motion, impact interaction, and compressive damage, and substantiates the operating principles of devices for gentle grain loading, including gravitational, cascade, and helical loading systems. It also presents the results of theoretical and experimental studies aimed at reducing grain damage, improving the uniformity of grain distribution, and increasing the efficiency and reliability of silo loading processes. The monograph focuses on technological solutions for the development and application of loading-distributing devices intended to preserve grain quality and enhance storage performance.

Recommended for researchers, engineering and technical personnel involved in grain storage, elevator equipment, and bulk material handling systems; as well as for higher education students in the fields of Agricultural Engineering, Electrical Engineering, and related technical specialties.

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INTRODUCTION

Grain farming is the fundamental basis of Ukraine's agricultural sector and one of the key components of national food security. The expansion of grain production must ensure a stable supply of food products for the domestic population while simultaneously forming a significant export potential. This export capacity plays an important role in strengthening the economic stability, resilience, and independence of the state under modern geopolitical and economic conditions.

Grain is among the most important food resources worldwide, serving as a primary raw material for both human nutrition and animal feed production. Ukraine occupies a leading position in the global grain market and is one of the largest exporters of this strategically important commodity. According to the results of the 2024/2025 marketing year, total exports of grain and oilseed crops from Ukraine reached 46.7 million tone's. Alongside increasing production and export volumes, the requirements for grain quality, safety, and preservation have become progressively more stringent. In this context, ensuring proper storage conditions and minimizing losses during transportation and handling are critical tasks for the grain industry.

For the storage of large batches of dry and cleaned grain at elevator enterprises, metal silos with flat reinforced concrete bottoms are widely used. These facilities are characterized by a high level of mechanization, with all technological operations related to grain transportation and handling being fully automated. However, during the movement of grain material prior to loading into silos, the grain repeatedly comes into contact with the working elements of various transport machines. Such interactions inevitably lead to mechanical and impact damage to a portion of the grain. It has been established that the share of damaged grain caused by bucket elevators can reach up to 12%, while damage induced by the moving elements of conveyors may amount to as much as 2.5% [1, 2, 3]. Consequently, by the time the grain reaches the silo loading inlet, a certain proportion of kernels already contains micro- and macro-damage.

The filling of cylindrical containers (silos) with grain or other bulk materials at elevator facilities represents the initial and critically important stage of the entire transport and storage system [4]. The technological cycle of silo operation generally includes three main stages: loading of grain into the silo, storage of the grain material

for a specified period, and subsequent unloading. Each of these stages has a direct influence on the quality and safety of the stored grain.

Loading of silos with grain is performed using various transport machines, including bucket elevators, belt and scraper conveyors, and chutes. The working elements of these machines, when interacting with grain, may cause damage to the kernels, especially to the embryo. Experimental studies have shown that damage to only 1% of grain embryos results in a corresponding 1% reduction in germination when such grain is used for sowing. In practice, this means that from sowing to emergence, up to 25% or even more of seeds may fail to germinate [1]. Such losses significantly reduce the efficiency of crop production and increase production costs.

During the loading process, particularly in the case of tall silos, grain falls from a considerable height. This free fall leads to an increase in the proportion of damaged kernels, with the most intensive damage occurring at the initial stage of silo filling. In addition, impact interactions between grain and the concrete bottom or walls of the silo further contribute to kernel damage. Such impacts negatively affect the sowing quality of grain and its storage stability. At a grain moisture content of 14–16%, the critical impact energy at which kernel damage occurs ranges from 0.11 to 0.16 J [1]. Under these conditions, field germination of seeds decreases by 17–23%. Moreover, gravity loading of silos promotes segregation and compaction of the grain bulk, which leads to caking and non-uniform density distribution. These phenomena adversely affect the food, feed, and technical qualities of grain and reduce the effective utilization coefficient of the silo's useful volume.

Mechanical and impact damage inflicted on grain by the working elements of technological machines and mechanisms has a pronounced negative effect on the quality of grain stored in silos. Damaged grain exhibits reduced resistance to long-term storage, characterized by intensified respiration processes and increased release of heat and moisture [5, 6, 7]. These factors contribute to the formation of self-heating zones within the grain mass, which may ultimately result in spoilage or complete loss of stored grain.

The degree of seed damage depends on a complex combination of factors, including the physical, mechanical, and biological properties of the grain; its condition during harvesting, post-harvest handling, and processing; the design and manufacturing

quality of agricultural and transport machinery; and the operational modes of these machines. Most of these factors are variable, leading to fluctuations in the grain's resistance to mechanical and impact loads.

Numerous experimental and analytical studies have confirmed that seeds with a high percentage of mechanical damage exhibit significantly poorer germination performance. According to the findings presented in [8], up to 30–40% of cereal seeds may fail to emerge due to microdamage. The primary cause of this phenomenon is injury to individual kernels under the action of the working elements of grain harvesting and handling equipment, which ultimately leads to a deterioration in grain quality and a reduction in crop productivity.

In order to reduce the proportion of damaged grain, especially during the loading of tall silos, it is necessary to employ specialized devices installed inside the silo. Such devices are designed to reduce the falling height of grain, dissipate its kinetic energy, and ensure a more uniform distribution of the grain mass during loading. Therefore, this study is devoted to the development, theoretical substantiation, and investigation of the operational principles of a loading–distributing device aimed at minimizing grain damage and improving the overall efficiency and reliability of silo loading processes.

CHAPTER 1. PROPERTIES OF BULK GRAIN MATERIAL

1.1 Physical and Mechanical Properties of Grain

The design and calculation of working elements of mechanisms and machines involved in the technological process of loading grain material into containers at modern elevators require preliminary technical justification of their structural elements, taking into account the technological properties of grain. These properties are determined by the morphological structure and the physical and mechanical characteristics of the grain and the grain mass as a whole.

The physical and mechanical properties of grain indicate its condition, structure, and responses to external forces acting upon it. Physical properties are, as a rule, characteristics that are observed or measured without transforming one substance into another. Mechanical properties of grain are indicators of its ability to resist loads and deformations, which determine its behavior during processing, cleaning, storage, and transportation. Physical and mechanical properties of grain are usually considered together.

The physical and mechanical properties of grain include: flowability (the ability of kernels to move freely relative to each other during the movement of the grain mass); self-sorting (separation of the grain mass by size during movement and falling into storage facilities); porosity (the presence of voids between grains); sorption properties (the ability to absorb vapors and gases); and thermophysical properties (heat capacity, thermal conductivity, and thermo-moisture conductivity). The physical and mechanical properties of grain entering storage are generally not constant and vary over a wide range depending on many factors [9, 10, 11].

During long-term storage of large grain batches at modern elevators, the following mechanical indicators are of particular importance: flowability, characterized by the angle of repose (the angle formed between the generatrix of the cone and its base during free fall of grain into a container) and the coefficient of friction; bulk density, which is a generally accepted indicator of grain quality; sorption capacity; aerodynamic properties (terminal velocity); geometric dimensions (length, width, and thickness); packing density of the grain mass (the ratio of the volume of intergranular space to the

total volume of the grain mass, expressed as a fraction or percentage); and grain elasticity. However, not all of these indicators equally affect mechanical damage to grain.

The greatest influence on damage is exerted by grain shape and surface condition, dimensional (linear and mass) parameters, moisture content, vitreousness, and shriveling. Mechanical damage to grain is also affected by the physical properties of the grain mass entering storage. These physical properties include flowability, hygroscopicity, uniformity, heat capacity, and thermal conductivity.

It is known that grain is a complex biological system whose components possess different mechanical properties, that is, different abilities to resist fracture while undergoing shape changes. The shape and surface condition of grain are highly diverse and, as a rule, differ by crop, species, and variety [12, 13]. However, even within the same species or variety, the shape and surface of grain can vary significantly depending on plant growth conditions and other factors.

According to shape, all seeds are divided into five classes: spherical, in which length, width, and thickness of the kernel are practically equal or differ insignificantly (peas, sorghum, millet, etc.); oval, where width equals length with significantly smaller thickness (lentils); elliptical, where thickness equals width with much greater length (soybeans and other legume seeds); elongated, where all three dimensions differ from each other (wheat, rye, barley, maize, etc.); and triangular, where all three dimensions may be equal or different, but the arrangement of planes forms a triangular shape (buckwheat).

Figure 1.1 shows the main types of seeds by shape [14]. Despite the fact that the grain of some crops does not have a regular geometric shape, the above groups cover the majority of field crops.

The surface of grain may be smooth and glossy, ribbed and rough, knobby or wrinkled, etc. These properties significantly affect grain transportation, cleaning, and sorting, as well as mechanical damage to kernels by the working elements of machines and mechanisms.

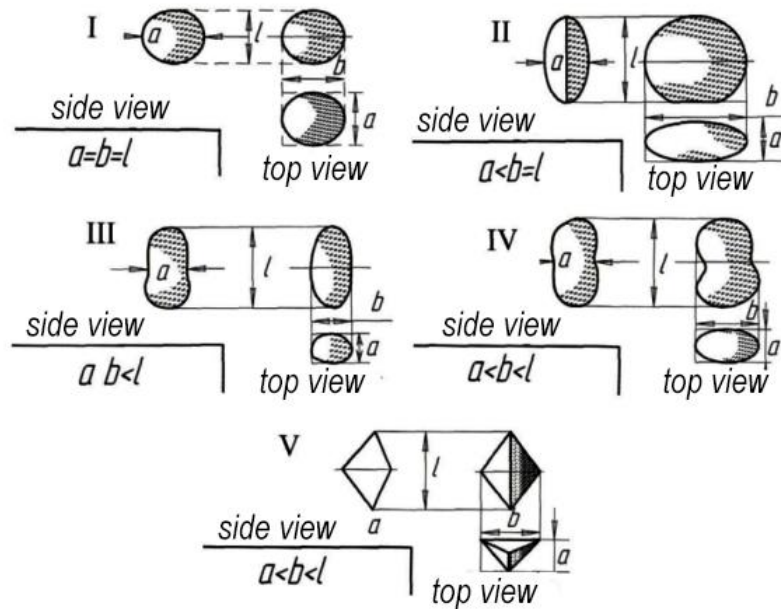


Figure 1.1 – Seed types by shape: I – spherical; II – oval; III – elliptical; IV – elongated; V – triangular; a – seed thickness; b – width; l – length.

The surface of grain depends not only on the inherent properties of a given plant but may also change under the influence of external conditions, depending on where the plant grew [9].

The physical and mechanical properties of grain also include indicators such as size and kernel weight class. As a rule, kernel size varies to a greater extent than grain shape. The size of grain of different crops is highly diverse, and its variability increases under the influence of individual characteristics of each plant and external factors. Grain size is determined by linear measurements (length, width, thickness). The length of seeds of cereal, legume, and technical crops varies widely—from 1.8 mm (millet) to 18 mm (oats), while for oilseed and technical crops it ranges from 2.5 mm (sugar beet) to 15 mm (sunflower) [9]. It has been established that the length of wheat kernels may be very long (>9 mm), long (8–9 mm), medium (6–8 mm), short (5–6 mm), or very short (<5 mm) [9, 15].

The width of seeds of cereal and legume crops ranges from 1.2 mm (millet) to 10 mm (maize), and for oilseed and technical crops from 1.7 mm (flax) to 8.6 mm (sunflower). At the same time, the thickness of seeds of cereal and legume crops may range from 1.0 mm (millet) to 8.0 mm (maize, peas), and for oilseed and technical crops from 0.5 mm (flax) to 6 mm (sunflower, soybean).

The diversity of seeds in size, absolute mass, and other characteristics is explained by differences in nutrition conditions, moisture supply, ripening, and formation on the plant, as well as, undoubtedly, by plant variety.

Large and small grain refer to dimensional characteristics, while heavy and light grain indicate mass characteristics.

In connection with the mechanization and automation of loading processes for large storage facilities (silos, metal bins, and warehouses), it is necessary to correctly use the physical and mechanical properties of grain. Thus, knowing the flowability of the grain mass makes it possible to completely avoid manual labor costs, especially when moving grain masses using bucket elevators, conveyors, and other installations used at modern elevators.

A significant influence on grain damage during its movement and free fall into tall containers is exerted by the tendency of the grain mass to lose homogeneity. This physical property is determined by the flowability of the grain mass and the heterogeneity of individual kernels within the bulk material. Self-sorting during free fall of light and dense kernels occurs because heavier kernels (maize, soybean, peas), having lower drag, descend vertically and quickly reach the bottom of the storage or the surface of the pile. Small, shriveled kernels have higher drag, so they descend more slowly and accumulate near the walls of the storage or roll down to the surface of the conical pile. The highest critical velocity is observed for heavy grain (16–17 m/s), for oats, barley, wheat, and rye it is 9–12 m/s, and for small grass and weed seeds it is 0.5–3 m/s [9]. Self-sorting of the grain mass negatively affects long-term storage. Loss of homogeneity of a grain batch leads to the development of adverse physiological and microbiological processes, which in turn cause self-heating of the grain mass.

Porosity of the grain mass, defined as the ratio of the volume of intergranular space to the total volume occupied by the entire mass, is of great importance for high-quality storage of grain mass in silos. Porosity depends on the shape and size of the crop's kernels, the surface condition of kernels, contamination of the grain mass, and the degree of caking in the pile.

The packing density of kernels in a pile is characterized by bulk density. Table 1.1 presents values of porosity and bulk density of grains of agricultural crops. The bulk

density of grain depends on crop type and moisture content. Porosity of grain masses in storage facilitates heat transfer by convection and the movement of moisture through the grain pile in the form of vapor. During long-term storage, the grain mass becomes compacted and its porosity decreases. This phenomenon must be taken into account when designing grain discharge devices from containers.

Table 1.1 – Bulk density and porosity of grain of different crops [9].

Crop	Bulk density, kg/m³	Porosity, %
Wheat	730 – 840	35 – 45
Rye	680 – 750	35 – 45
Barley	580 – 700	45 – 55
Oats	400 – 550	50 – 70
Buckwheat	560 – 650	50 – 60
Millet	680 – 730	30 – 50
Maize (Corn)	680 – 820	35 – 55
Rice	440 – 550	50 – 65

Under the influence of moisture, the linear dimensions of kernels change. Thus, with an increase in moisture content, the width increases significantly (by 10.8%) and the thickness increases by 6.2%. The length is more resistant to the effect of moisture, increasing by about 5.2% [16]. It has been established that microdamage in moist grain is greater than in dry grain; moisture also leads to changes in the size of the embryo, which in turn contributes to an increase in its damage.

The mass of 1000 kernels varies moderately both among different crops and within specific economic and botanical groups, depending on varietal diversity and soil–climatic as well as agrotechnical growing conditions of a given crop. The mass of 1000 kernels is one of the most stable indicators within a variety [9]. Grain uniformity is the degree of homogeneity of individual kernels forming the grain mass according to a particular indicator. Table 1.2 presents the absolute mass of seeds of selected agricultural crops.

Table 1.2 – Absolute mass of seeds of the main agricultural crops [9].

Crop	Mass of 1000 grains, g	Crop	Mass of 1000 grains, g
Wheat	22 – 42	Rice	24 – 31
Oats	20 – 42	Millet	6,0 – 6,5
Rye	13 – 32	Peas	155
Maize (Corn)	205 – 345	Sunflower	53 – 65
Barley	31 – 51	Buckwheat	235

During transportation of the grain mass to the inlet of a silo structure, the predominant type of friction is sliding friction, which is evaluated by the dynamic coefficient of external friction. The dynamic coefficient of external friction for wheat, barley, and maize grain on various materials ranges from 0.3 to 0.5 [9].

An important characteristic of grain is its elasticity. Grain elasticity depends on its chemical composition. It is known that seeds with a higher protein content exhibit greater elasticity. Therefore, the higher the grain moisture content, the lower its elasticity. The elastic properties of grain are characterized by the coefficient of velocity restitution after a grain impacts a solid stationary surface.

The coefficient of velocity restitution for dry peas is 0.6–0.7, whereas for moist peas it is almost twice as low [9].

An important factor determining the quality of grain delivered to storage facilities is its moisture content. The moisture content of grain plays a significant role in the technological process of loading silos with grain cargo.

A characteristic feature of freshly harvested grain crops is a considerable non-uniformity of moisture among individual kernels. Thus, in a batch of wheat grain with an average moisture content of 17.7%, the moisture variation among individual kernels ranges from 14% to 24% [11, 18].

Therefore, when designing transport and loading devices, as well as when setting technological adjustments and operating modes, it is advisable to take into account the morphological structure and the physical and mechanical properties of grain.

1.2 Bulk Agricultural Materials

From a physical point of view, a bulk agricultural material is a dispersed two-phase system that exists at certain phase ratios. Quantitatively, this ratio can be evaluated by the packing density coefficient of kernels. This coefficient is the main parameter characterizing bulk grain material as a two-phase dispersed system:

$$K = \frac{V_T}{V} = \frac{\gamma}{\rho}, \quad (1.1)$$

where V_T – is the volume of the solid phase, m^3 ; V – is the volume of the bulk material, m^3 ; ρ – is the density of the solid phase, kg/m^3 ; γ – is the bulk density of the grain material, kg/m^3 .

The value of the packing density coefficient depends on the conditions under which the bulk grain material is formed in a cylindrical container. To obtain a stable structure, it is necessary that each kernel has no fewer than six contacts (bonds).

When filling cylindrical containers, two types of loading can be used: gravitational and inertial. At a pile height of $H=2.5-3$ m, the inertial method of packing is generally applied. For different crops, the values of the packing density coefficient are presented in Table 1.3.

Table 1.3 – Values of the packing density coefficient [9].

Crop	Value of coefficient K
Wheat	0,555 – 0,645
Oats	0,55 – 0,64
Buckwheat	0,54 – 0,62
Barley	0,495 – 0,595
Maize (grain)	0,555 – 0,615

Bulk agricultural materials are a static assembly of individual kernels whose random orientation in space is determined by gravitational, frictional, and interparticle

forces arising from the interaction of moving kernels with one another. These materials possess properties that make it possible, with relatively low energy input, to mechanize practically all technological processes at an elevator related to conveying and mixing.

The properties of individual phases of bulk grain material can be described by their parameters; however, describing the nature of the properties of bulk grain material that is in continuous motion is considerably more complex. These properties represent a function that describes the parameters of the phases and the parameters of the static state of the grain material:

$$\Phi_i = L_i(<x_i>, <y_i>), \quad (1.2)$$

where Φ_i – are the properties of the bulk grain material; L_i – is an operator that depends on the parameters of the bulk grain material x_i and on the parameters of the solid and air phases y_i .

In practice, two groups of properties of bulk materials are used. The first group, which is basic, includes structural–mechanical, force-related, and frictional properties. The second group characterizes the processes occurring in bulk material, reveals their main relationships, and is used for technological calculations and for developing methods to control the processes taking place in bulk material. This group includes electrophysical, thermophysical, and aerodynamic properties.

Bulk agricultural materials consist of individual particles (solid phase). The solid phase is characterized by the following six main groups of properties: measurable, structural, frictional, thermophysical, aerodynamic, and electrophysical [20].

The first group includes parameters whose values are determined by measurement. These include the particle-size (granulometric) composition, which can be described by the following distribution law:

$$df = (x_i) d_i. \quad (1.3)$$

The parameter x_i may take one of the following values: d – size, S – surface area, m – mass of kernels. Considering that kernels in most real bulk materials have irregular

shapes, equivalent values are introduced: $d = d_e$, $S = S_e$, replacing the real kernel with a sphere of mass M_e , equal to the mass of the kernel.

Structural parameters of the solid phase of bulk grain material can be considered as parameters of elastic bodies. The behavior of grain during loading and storage in silo-type containers differs. For example, when grain falls onto the flat bottom of a container, it is characterized by a coefficient of restitution [21]. In piles under relatively low pressures, the behavior of bulk material can be fully described by three parameters: density ρ , Young's modulus E , and Poisson's ratio μ .

Bulk agricultural materials are characterized by the following physical and mechanical properties: size and shape of kernels; density; mutual mobility of kernels; coefficient of friction; and angle of repose of the grain bulk [20].

The frictional properties of grain, depending on the degree of dispersion, are determined by external or molecular forces [22]. The parameters characterizing these forces are divided into two groups:

- for large kernels ($d > 100 \mu\text{m}$): coefficient of static friction and coefficient of kinetic friction;
- for small kernels ($d < 100 \mu\text{m}$): static and impact detachment forces of kernels.

The manner of energy transfer in bulk material is largely determined by friction and adhesion forces at the contact points between kernels.

The granulometric characteristics of the solid phase of bulk grain material depend on the kernel dimensions of the crop (l , b , a) and on the equivalent diameter of kernels, which is determined as:

$$d_{eq} = \sqrt{\frac{6V_t}{\pi}}, \quad (1.4)$$

The shape and surface characteristics of kernels used in calculations are defined by the shape factor Φ :

$$\Phi = \frac{S_t}{\pi(d_{eq})^2}, \quad (1.5)$$

where S_t is the surface area of a kernel of the bulk grain material.

The frictional properties of ideal materials, which include grain of various agricultural crops, are determined by the coefficients of external and internal friction and the coefficient of adhesion.

When silos are filled with grain material, a grain pile is formed. To characterize bulk material in a pile, the void ratio ε or porosity m_{mm} is introduced. To study the behavior of piles, it is most appropriate to use the packing density coefficient, for which it is necessary to know the density of the solid phase and the bulk density of the material (for wheat, $\gamma=800 \text{ kg/m}^3$).

The packing density coefficient of kernels of bulk grain material is not constant and varies depending on the conditions of formation of the bulk material in a silo container, the flow conditions, boundary conditions of the flow, etc.

A characteristic feature of the packing density coefficient is that during relative displacement of layers of bulk material in a pile, its value in the shear zone attains a certain constant value K_{cr} , which lies between the minimum and maximum values. Moreover, the smaller the average kernel size, the closer K_{cr} approaches its minimum value.

1.3 Resistance of Grain to Mechanical Loads

At elevator facilities, the working elements of transport machines interact with grain materials that possess different rheological properties. During the interaction of grain material with the working elements of transport machines, all types of mechanical forces act on it: static forces, i.e., forces that increase gradually; dynamic forces, when loading occurs by impacts; and alternating forces, which change in magnitude or in both magnitude and direction. For grain cargoes, interaction with working elements is characterized by the distribution of interaction forces and contact zones, which are described by the laws of mechanics.

During harvesting and post-harvest handling, seeds are subjected to mechanical effects (abrasion, compression, impact) by the working elements of machines and

transport devices. The amount of mechanical damage to grain material caused by machine working elements is the result of two factors: the action of the working elements on the grain and the inherent strength of the grain itself.

Studies of grain of various crops and varieties have shown that the natural mechanical strength of grain varies within a very wide range. Therefore, mechanical strength depends on the crop, variety, grain moisture content and size, the type of mechanical force (impact, compression, shear, friction), the orientation of the grain, and the type of material from which the working elements of transport machines are made. Consequently, for the same working element under identical loads, different assessments of the performance quality of a transport machine may be obtained depending on the mechanical properties of the grain [23].

Most often, grain kernels at elevators are subjected to impact loads, which can be divided into two groups.

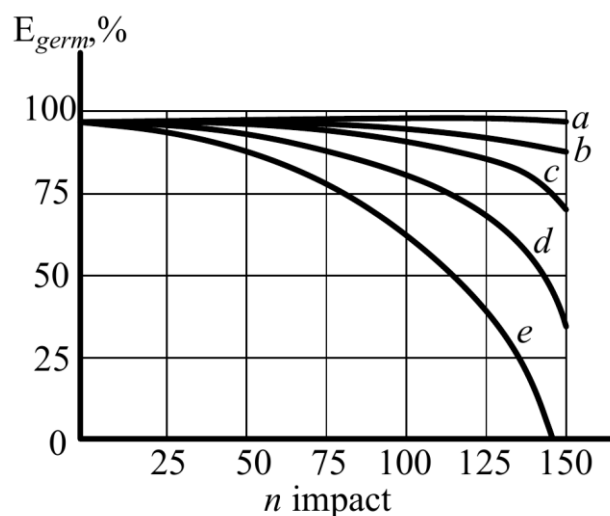
The first group includes loads that depend on the mass and velocity or the forces of the working elements of conveyors acting on the grain during its movement. The second group includes all cases of free impact, where the force of action is determined by the velocity and mass of the grain itself (for example, impact of grain against the conveyor casing, impact due to a reduction in clearances between the working element of a bucket elevator and its head casing, etc.).

Under intense mechanical impact, grain is crushed and becomes unsuitable for long-term storage. However, even the kernels that remain visually intact after impact may lose their germination capacity before any cracks appear in the husk.

Figure 1.2 presents a graph showing how impact affects the germination energy of wheat grain with different moisture contents. The number of mechanical damages to seeds increases under repeated impact action.

If the mechanical action (in terms of the number of impacts or velocity magnitude) is 2–3 times higher than the permissible level, cracks may appear on the grain surface [24, 25, 26]. Figure 1.3 shows the dependence of the strength of wheat, oat, and pea kernels on moisture content. Grain strength is characterized by the drop height of a 200 g weight at which cracks appear on the seed after impact. The magnitude of impact loads is not the same for different agricultural crops, and for grain of the same crop it depends

on moisture content; the strongest grain is that whose moisture content is close to the standard (conditioning) level.



a – 10%; *b* – 15%; *c* – 25% ; *d* – 30% ; *e* – 30%

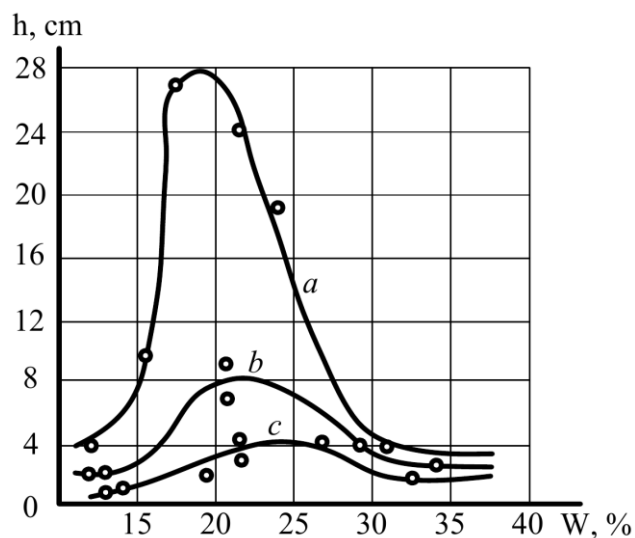
Figure 1.2 – Effect of impact on seed germination energy at different moisture contents

Requirements for grain products stored for long periods are becoming more stringent each year, particularly with respect to preserving commercial quality. Therefore, proper storage, careful loading, and unloading of silos ensure maximum quality and value of grain crops.

Impact and mechanical damage to grain at elevators, especially to seed material, is highly undesirable, as it increases losses of expensive seed material, reduces yields, and decreases the commercial and consumer value of grain grown from damaged seeds.

A wide variety of transport equipment is used at elevators (chain conveyors, belt conveyors, bucket elevators, screw conveyors, etc.). From literature sources it is known that the total breakage coefficient caused by transport equipment is about 2.2% [3]. The greatest grain damage occurs in bucket elevators. Let us consider the nature of grain damage during bucket loading. Grain injury occurs as a result of an impulse arising from the difference in the direction vectors of the kinetic energy of kernels and the working elements of the bucket elevator. If the grain cargo is fed in the direction of bucket loading, impact impulses are reduced by 20–30% compared to feeding the material

against the direction of bucket movement [3,7]. As a result, impact impulses are largely dissipated upon collision with the bucket, and the grain is practically not damaged.



h – drop height of the load; ω – moisture content; a – peas; b – rye; c – wheat

Figure 1.3 – Change in seed strength depending on moisture content

Belt conveyors are an important element of elevator facilities. They are used to feed grain material to silos for short-term and long-term storage. The advantages of belt conveyors are obvious, but they also have drawbacks. First of all, these include direct contact of the traction element with structural components, high transport speed, steel scrapers, kernels entering the engagement between the drive sprocket and the traction chain, and vertical conveying of grain material. All these drawbacks lead to kernel injury during conveyor operation due to grain material entering the space between the chain and the conveyor casing [27].

Screw conveyors are widely used at elevators as transport devices. Figure 1.4 shows the movement of grain material in a screw channel. It has been found that with an increase in screw rotational speed, grain damage increases due to intensified friction against moving and stationary surfaces of the conveyor [28].

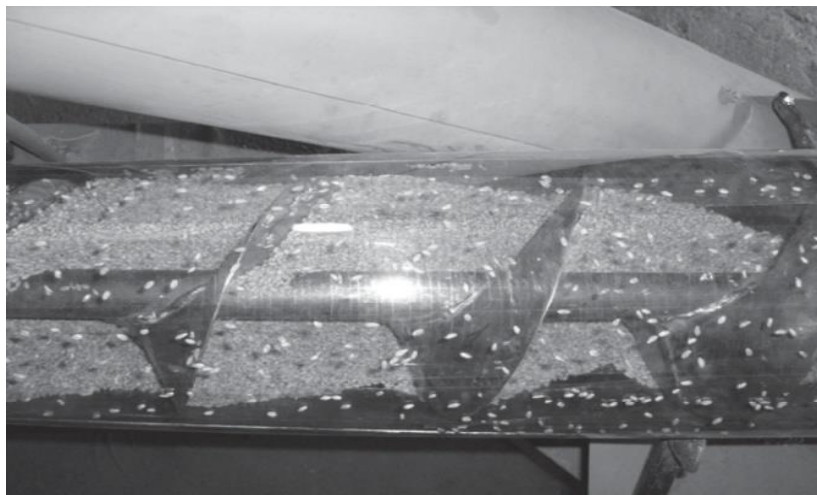


Figure 1.4 – Movement of grain in a screw conveyor

The efficiency of screw conveyors depends on many factors related to the conditions in which they are used. It should also be noted that the design and kinematic parameters of screw conveyors significantly affect the process of transporting grain material without causing damage. Articles [28, 29] indicate that grain damage depends on the parameters of the screw conveyor, specifically on the clearance between the screw working element and its casing. Figure 1.5 shows the locations where kernels are damaged by the screw working element of the conveyor.

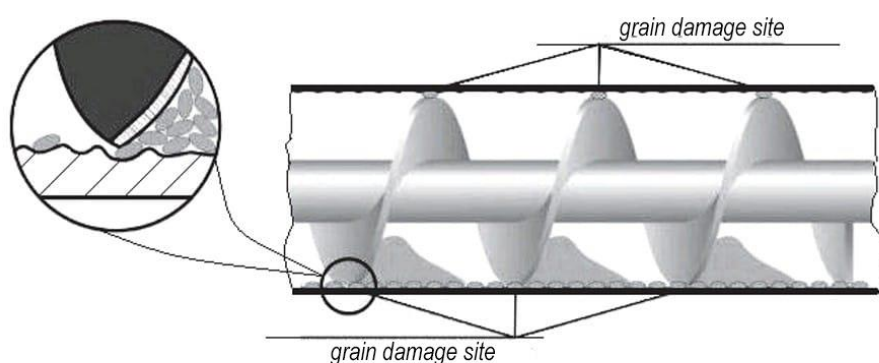


Figure 1.5 – Interaction of the conveyor screw with grain

In search of ways to reduce the grain breakage coefficient, experiments were conducted by the company SE “Zernova Stolytsia” [3] to determine how the transport speed of conveyor traction elements affects the increase in grain breakage (Figure 1.6). It was found that the contact area between the product and the traction element should be minimal. To achieve this condition, it is necessary to reduce the conveyor width while

increasing its height so that the grain layer is higher and resistance with the traction element is minimized, which positively affects the quality of the transported grain material.

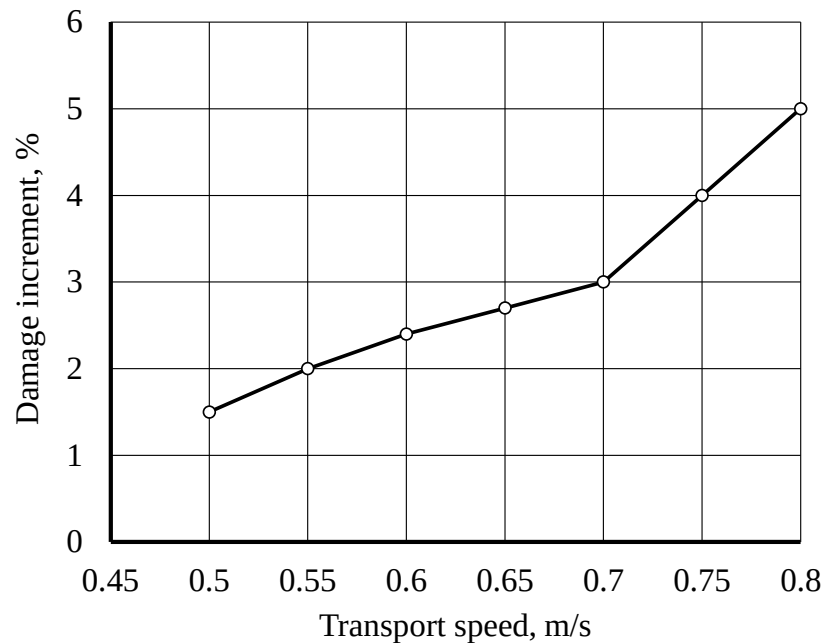


Figure 1.6 – Dependence of the increase in grain damage on its transport speed by a belt conveyor

Depending on shape, size, structure, and the condition of the covering оболонки, grain is damaged in different ways. Mechanical and impact damage, especially to seed grain, reduces germination due to damage to the embryo and infection of damaged seeds by bacteria, fungi, mites, and other diseases and pests.

It has been established that damage to wheat of up to 10% leads to a yield reduction of 1 centner per hectare; in turn, damage to the embryo results in a yield reduction of cereal crops by 7.1 centners per hectare, while the yield of severely damaged seeds does not exceed 13.9–15.3 centners per hectare [7].

During storage of damaged grain in silos, significant losses may occur due to intensive respiration, active action of bacteria, fungi, mites, and other negative factors [24]. Therefore, all silo structures are equipped with active ventilation systems.

1.4 Classification and Methods for Determining Mechanical Damage to Grain

Mechanical damage to grain material intended for long-term storage significantly affects its storability, germination capacity, and the yield of finished products during processing.

Mechanical damage to grain can be divided into three main groups according to the scale and nature of deformation: micro-damaged, macro-damaged, and severely damaged (broken) grain. There is a distinction between macro-damaged and micro-damaged grain. Its essence lies in the fact that crushed (longitudinally or transversely), cracked, flattened, or dehulled kernels differ significantly from intact kernels in their physical and mechanical characteristics (size, mass, shape) and aerodynamic properties. Therefore, most of them can be easily separated using grain cleaning and sorting machines.

Macro-damage is visible to the naked eye, but such kernels are not split into separate parts. These may include deep cracks in the hull, dents, or partial removal of the fruit coat.

Micro-damaged kernels do not exhibit such visible differences and cannot be separated from undamaged grain, since internal tissues are damaged or microscopic cracks appear in the hull, which cannot be seen without special equipment. Internal cracks arise not only from mechanical damage or impact but also from abrupt temperature changes during ripening or drying. Micro-damage occurs at the points where the kernel stalk is attached, during rupture of the embryo seed coat, and with the formation of so-called “bruises”. “Bruises” form as a result of the rupture of internal cells when an impact is applied to immature kernels or kernels with high moisture content, as well as when kernels fall from a height onto the concrete floor of a silo. Such injuries increase the intensity of grain respiration by two times and its susceptibility to microorganisms by 10–12 times [30]. On modern grain cleaning and sorting machines, such micro-damaged kernels cannot be distinguished from undamaged grain.

Broken grain (severely macro-damaged) exhibits complete or partial destruction of kernel integrity. Such kernels may be crushed, with chipped parts of the endosperm, cotyledon, or embryo.

Under the action of dynamic and static loads arising during loading and unloading of grain material from silos, grain resists destruction to a certain extent and becomes damaged. Studies have shown that when the deformation of winter wheat kernels increases from 0.1 to 0.5 mm, the degree of damage increases from 0.5% to 13.7% [31]. At the same time, laboratory germination of winter wheat kernels decreases by approximately 6.4% at a deformation of 0.1 mm, and by 34.7% at a deformation of 0.5 mm [31].

The dependence of changes in germination and damage of winter wheat kernels on the magnitude of deformation is shown in Figure 1.7.

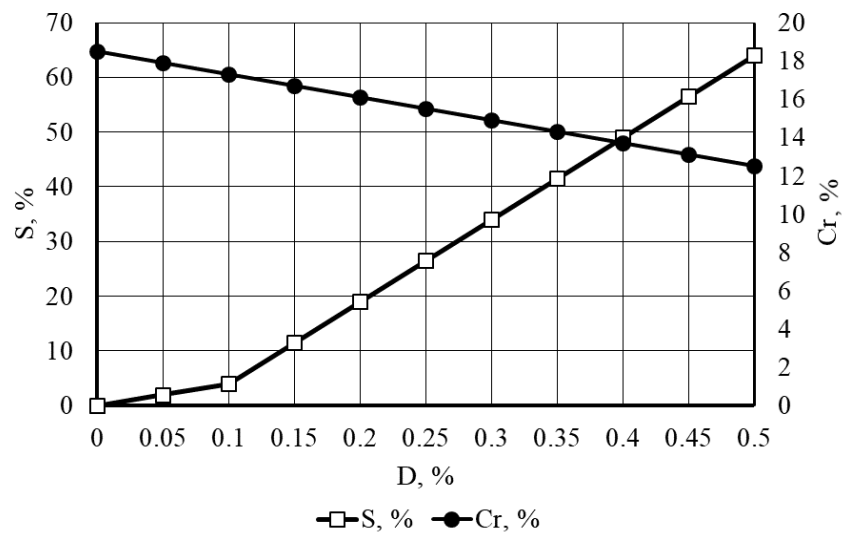


Figure 1.7 – Dependence of changes in germination and damage of winter wheat on the magnitude of its deformation

The presented graph shows that kernel deformation depends on the forces acting on winter wheat kernels and on their moisture content. This means that in order to obtain high-quality seed grain, the deformation of grain material entering storage in silos must be minimized.

The degree of damage strongly depends on the physical, mechanical, and biological properties of seeds, which implies that different crops may be damaged to different extents when loaded into silos for storage. Article [32] indicates that among cereal crops, maize is damaged to the greatest extent, followed by rye, soft wheat, barley, and durum wheat. Grain entering elevator storage, in addition to mechanical damage,

may also be subjected to thermal damage due to excessively intensive drying. When loading silos with grain material, it should be borne in mind that the level of damage caused by the working elements of machines and mechanisms at elevators increases sharply if the seed is too dry or, conversely, too moist. Based on this, it is recommended to store cereal crops at a moisture content of 14–20% and maize at 12–22% [33].

To improve the sowing qualities of maize seed, study [33] recommends chemical pre-sowing treatment (seed dressing) of damaged seeds, which, according to the authors, makes it possible to increase field germination by 12–32% and maize yield by 15.4–26.3% compared with untreated seed material. In order to reduce the level of grain damage, a number of measures should be applied: drying maize under mild temperature regimes, performing less intensive separation, and, where possible, reducing the movement of grain masses by bucket elevators and conveyors at elevators.

Figure 1.8 presents a classification of mechanical damage to cereal grain. This classification takes into account the physical and mechanical properties of grain entering elevator storage and reflects all possible types of grain damage.

To assess the performance quality of conveyors and to characterize the grain mass, it is necessary to determine micro- and macro-damage to grain. Mechanical damage to grain can be identified by various methods, ranging from simple visual inspection to high-technology approaches using non-destructive instruments.

Traditional methods for determining grain damage include organoleptic, staining, and biological methods [34].

In the organoleptic method, the amount of macro-damaged grain is visually determined using a magnifying glass or a microscope; damaged kernels are manually separated from a sample. In some cases, the smallest micro-damaged kernels remain unnoticed. To reveal all types of damage, grain is stained; this technique makes it possible to identify hidden injuries and cracks in the endosperm. For staining grain, “Fast Green” FCF or iodine is used; iodine stains only the exposed starch at locations where the seed coat is damaged.

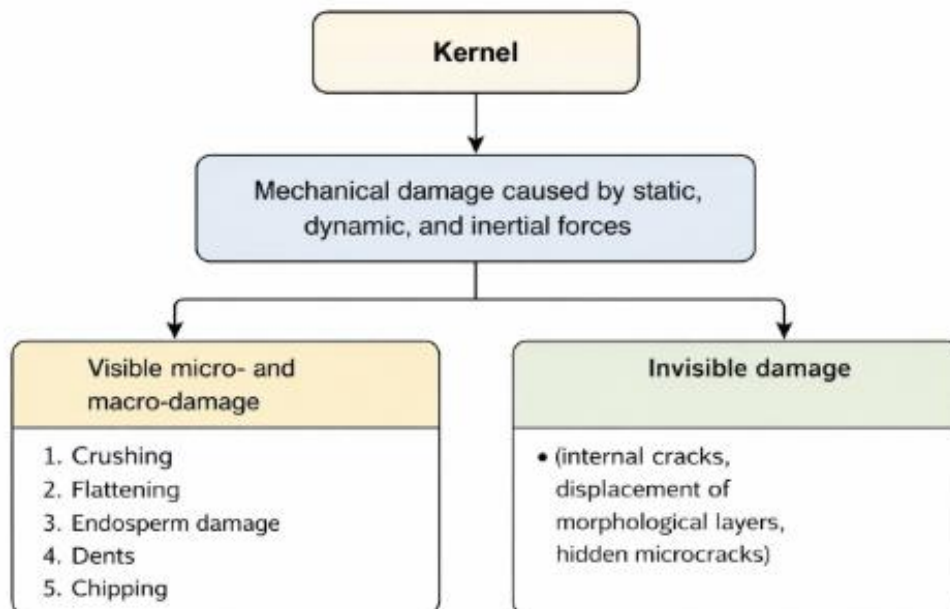


Figure 1.8 – Classification of mechanical damage to grain

The organoleptic method allows rapid and fairly accurate determination not only of the total amount of macro-damaged kernels, but also their classification by damage type. However, this method does not make it possible to determine the total amount of hidden internal damage to kernels; such damage can only be identified indirectly, by the degree of reduction in germination. This method is not universal and has a significant drawback: it provides only relative values of the number of micro-damaged kernels in a batch, while reduced germination may also be caused by other factors. In addition, this method does not allow identification of the types of micro-damage in individual kernels.

The biological method makes it possible to determine the effect of different types of micro-damage on sowing and productive qualities of seeds through comparative evaluation of germination energy, laboratory or field germination, initial growth vigor, completeness of seedling emergence, biometric indicators (height, weight), and yield of grain and plant biomass.

In addition to traditional methods, modern and innovative approaches are also used. These include computer vision and artificial intelligence, hyperspectral analysis, radiography and tomography, and acoustic emission techniques.

Computer vision and AI employ high-resolution cameras and neural networks for automatic recognition and classification of damage on conveyor belts.

Hyperspectral analysis enables detection of hidden internal cracks and spoilage foci based on the spectral characteristics of reflected light.

The most accurate methods for detecting internal microcracks without destroying the kernel are those using radiography and tomography.

Another method used to detect micro-damage is based on recording sound waves generated during deformation or cracking of grain under load. This approach is divided into three techniques: ultrasonic flaw detection (active method), acoustic emission (passive method), and laser-ultrasonic diagnostics.

In the active diagnostic method, high-frequency sound waves are transmitted through the grain. When a sound wave encounters microcracks (voids or air layers inside the kernel), it is reflected or scattered, since air has different acoustic properties than grain tissue. Sensors in the device record echoes or changes in amplitude and velocity of the transmitted wave. The presence of cracks significantly attenuates the signal detected by the instrument.

In the passive method, acoustic micro-impulses generated within the grain itself are recorded. The formation or expansion of a microcrack is accompanied by the release of energy in the form of elastic waves, which are detected by sensitive sensors.

Laser-ultrasonic diagnostics is designed to detect internal grain damage [35, 36]. In this method, a laser pulse is used to generate an acoustic wave inside the grain without direct mechanical contact.

In all these methods, specialized instruments analyze the wave transit time through the grain and its attenuation. Modern systems use machine-learning algorithms to compare the obtained acoustic “signatures” with reference patterns of intact and damaged grain (spectral analysis).

For acoustic diagnostics of grain microcracks, ultrasonic flaw detectors (e.g., UD series or analogs from Novotest, Grow-Technique), acoustic analyzers (devices measuring grain elasticity parameters), and acoustic emission (AE) systems are used. Leading manufacturers of such equipment include Mistras Group and Vallen Systeme; these systems make it possible to detect crack initiation in real time.

The application of modern methods for diagnosing mechanical damage to grain opens broad opportunities for improving the accuracy of quality control of grain products

at all stages of post-harvest processing, transportation, and storage. The combination of traditional assessment methods with digital, optical, acoustic, and intelligent technologies makes it possible not only to promptly detect external and internal defects of kernels, but also to predict possible changes in their sowing, technological, and commercial properties during further use.

Such approaches are of particular importance for seed grain, where even minor internal damage may lead to a significant reduction in germination capacity and germination energy. The use of high-precision non-destructive testing methods makes it possible to detect microdefects in a timely manner that cannot be identified visually but significantly affect grain viability. This creates a basis for improving sorting systems, increasing the efficiency of post-harvest processing, and reducing losses of high-quality material.

The integration of automated damage detection systems into the technological lines of elevators and grain-processing enterprises will contribute to improving the reliability of production processes, reducing quality control costs, and ensuring consistently high grain preservation performance. In the future, the development of such technologies will be associated with the broader implementation of artificial intelligence systems, machine learning, and digital monitoring, which will make it possible to move from periodic inspection to continuous real-time analysis of the condition of the grain mass.

Thus, improving methods for detecting macro- and microdamage in grain is an important direction in the development of modern grain storage technologies. The integrated use of organoleptic, biological, optical, acoustic, and tomographic methods provides a more complete assessment of grain condition, increases the objectivity of control, and creates conditions for preserving grain quality, reducing losses, and improving the overall efficiency of grain management systems.

CHAPTER 2. STRUCTURES FOR GRAIN STORAGE

2.1 Classification of Grain Storage Facilities

For high-quality storage of large batches of grain, especially seed grain, special grain storage facilities are used in which the physical and physiological properties of grain material are taken into account most effectively.

Grain storage facilities are classified according to many criteria: by storage method; by the materials from which they are made; by the degree of mechanization of all technological operations (mechanized, semi-mechanized, non-mechanized); by the availability and type of active aeration systems (duct, floor, portable, etc.); by storage duration; and by spatial dimensions [37–40].

According to the construction material, grain storage facilities are divided into reinforced concrete, metal, brick, and more rarely glass-like and wooden structures. In addition, grain storage facilities may be cylindrical, square, or conical, and by the type of bottom-flat or conical. By shape, they can be vertical or horizontal, and by purpose-intended for storing grain, flour, or bulk materials. In grain storage facilities, grain may be stored temporarily (from several days up to one month), for a medium term (one to three months), or long-term (more than 30 days).

During temporary storage, grain is kept under sheds or in heaps. This storage method is used during periods of mass grain harvesting.

For long-term storage of grain, elevators are used. They ensure cleaning and drying with maximum efficiency and the best preservation of grain. Unlike warehouses with stationary mechanization, elevators are compact enterprises. Their compactness is achieved due to the great height of the structures. An elevator is the most advanced grain storage facility, fully mechanized, with minimal manual labor, more efficient use of building volume, lower grain losses, better isolation from the external environment, and a smaller construction footprint [41,42]. In addition, elevators are equipped with reliable and safe fire protection systems as well as protection against rodents. The installed ventilation system with a regulated microclimate is designed to store the maximum possible amount of grain reserves without loss of their food and nutritional value.

According to storage capacity, elevators are divided into small, medium, and large. Small facilities store up to 10 thousand tone's of grain or oilseeds in stationary containers. Medium elevators store from 10 to 50 thousand tone's of grain. Large elevator enterprises can store from 50 to 100 thousand tone's of grain or more at one time.

The main structures of an elevator include the working tower, silo block, receiving and discharge devices. The working tower houses bucket elevators, scales, grain cleaning machines, gravity-flow and aspiration equipment, as well as drive and tension stations of elevator conveyors. In modern elevators, grain material is stored in metal silos.

2.2 Metal Silos for Grain Storage

Metal silos for grain storage are welded or prefabricated metal containers equipped with ventilation systems and layer-by-layer temperature monitoring of grain material. The main advantage of such silos is their high level of construction and operational reliability, complete mechanization of loading and unloading operations, and a wide range of standard sizes. The disadvantages of metal silos include, firstly, susceptibility to corrosion under the influence of external and internal factors, which requires regular maintenance of metal structures; secondly, the possibility of moisture condensation inside the containers during operation (necessitating thermal insulation); thirdly, grain damage during loading and unloading; and fourthly, high horizontal pressure on silo walls during grain discharge [43, 44].

The use of metal silos for grain storage prevents its destruction by birds and rodents. A properly constructed silo is a sealed container that protects grain material from adverse atmospheric effects. When a silo is fully loaded with dry and cleaned grain, a process of self-preservation occurs during the first months, as a result of which living components enter an anabiotic state. Therefore, grain mass losses do not exceed regulatory limits.

Vertical metal silos may be: rectangular, made of corrugated steel panels; rectangular, made of smooth panels; silos with flat concrete bottoms; silos with conical

bottoms; cylindrical silos made of corrugated panels with bolted joints; cylindrical silos made of smooth panels with bolted joints; and spiral-folded silos.

Vertical silos are installed at elevators. They are divided into rectangular and cylindrical types. Figure 2.1 shows the main types of metal silos.

Rectangular silos are classified by wall type, bottom type, and roof. The first type is a rectangular silo made of corrugated steel panels (Fig. 2.1a) [45]. The second type is a rectangular silo made of smooth steel panels (Fig. 2.1b). From the standpoint of land-use efficiency, rectangular silos are the most effective and are usually used as intermediate storage in technological processes.

Cylindrical silos are classified by the type of bottom, walls, and roof. Silos with flat and conical bottoms are distinguished [45].

Flat-bottom silos (Fig. 2.1c) are intended for long-term storage of dry and cleaned grain (maize, wheat, barley, etc.). Such structures are installed on concrete foundations using pile foundations or on crushed-stone bases, depending on geological conditions.

Concrete silos are very reliable and durable but extremely expensive to construct. Polymer silos are used in polymer sleeves for grain storage. Distributor silos are designed for dosing and distributing materials.

Silo design ensures stable operation and high-quality maintenance. The main technical characteristics of silos include dimensions (diameter, height), volume (from several to thousands of cubic meters), materials (galvanized steel), structural features (flat or conical bottom, roof, frame), and equipment (ventilation systems, temperature and level sensors), which ensure safe grain storage.



a



b



c



d



e



f



g

a – rectangular with corrugated steel panels; *b* – rectangular with smooth panels; *c* – flat-bottom; *d* – conical-bottom; *e* – cylindrical with corrugated panels and bolted joints; *f* – cylindrical with smooth panels and bolted joints; *g* – spiral-folded silo.

Figure 2.1 – Types of vertical metal silos [39]

Figure 2.2 shows flat-bottom silos located in the Poltava region. Such silos are equipped with active ventilation systems and have frames made of corrugated steel.



Figure 2.2 – Silo structures with flat concrete bottoms

Conical-bottom silos are intended for complete gravity discharge. The supporting structure of such silos is made of metal profiles that bear the entire weight of the silo and the stored product. Loading and unloading are carried out through central openings at the top and bottom [46].

Depending on wall design, cylindrical metal silos may be solid-wall, corrugated-panel with bolted joints, smooth-panel with bolted joints, or spiral-folded.

Solid-wall metal silos are used for storing flour and cement, with volumes ranging from 60 to 70 m³.

Silos made of corrugated panels assembled with bolted joints (Fig. 2.1e) are used for grain storage with volumes from 100 to 15,000 m³ and are intended for long-term storage. Corrugated panels increase strength and stiffness under transverse bending. Moreover, such panels exhibit structural anisotropy, as stiffness characteristics along and across corrugations differ significantly: the moment of inertia in the horizontal

direction is 70 times greater, and the section modulus is 9.7 times greater than in the vertical direction [38].

In recent decades, there has been a trend toward constructing silo blocks from corrugated galvanized and enameled steel for grain storage (Fig. 2.3). Such silos provide uniform bulk density loading, mechanized transfer between silos, recirculation within a silo, prevention of internal condensation, flexible aeration regimes, energy savings during unloading, mechanized topping-up, automation and overload control with alarms, electronic temperature monitoring with centralized control and data archiving, protection against precipitation, birds, and rodents, and ease of maintenance of aeration and discharge systems.



Figure 2.3 – Galvanized steel silo blocks

Silos made of smooth panels with bolted joints (Fig. 2.1f) are used for storing bulk materials, usually with conical bottoms and volumes from 25 to 550 m³. To ensure rigidity, increased shell thickness is required, with thicker panels installed at lower levels.

Spiral-folded silos (Fig. 2.1g) are assembled without bolts; panels are joined using double-folding technology (Fig. 2.4), providing additional horizontal rigidity and airtightness with minimal metal consumption.

Metal flat-bottom silos of the “SPA” type, manufactured by the Polish company Unia, are designed for storing grain, oilseed, legume crops, and granulated products. The

diameter ranges from 6 to 31.8 m, and capacity from 96 to 15660 t (wheat equivalent). For example, SPA 22,5/19 silos have a total volume of 9734 m³, usable volume of 9724 m³, load capacity of 7585 t, total height of 29,36 m, annual electricity consumption of 16500 kWh, annual labor costs (for 6 months of storage) of 2160 hours, and electricity costs of 1850 UAH [47].

Flat-bottom silos made of smooth metal sheets have advantages due to their smooth internal walls, which prevent grain bridging and facilitate unloading.

For large-scale storage, silo temperatures should be maintained between 5 and 10 °C. When temperatures exceed 15–20 °C, the risk of pest development increases sharply. Optimal moisture content for long-term storage is 12–14% for wheat and maize and 6–8% for oilseeds [48].



Figure 2.4 – Spiral-wound silo with folded joints

Silos are installed on shallow foundations or on supports with conical bottoms. Integrated storage complexes (Table 2.1) may be equipped with drying units using gas, liquid, or solid fuel; cleaning facilities; and mini-processing plants for flour, oil, alcohol, etc., with capacities from 500 to over 30000 t.

Metal silos are erected using various construction methods. Early silos were assembled by welding metal sheets on temporary frames — a labor-intensive method.

Modern methods include roll-forming of steel sheets mounted on factory-made frames and spiral winding, where silo walls are formed by winding steel strips joined by folds. Currently, silos with corrugated steel walls are the most common, as they provide higher strength and lower weight compared to smooth-sheet designs.

Table 2.1 – Types of grain storage facilities with capacities from 500 to 30000 t and more

Type of structure	Silo capacity, t	Number of silo sets, pcs	General view
K-1700	40	10	
	125	6	
	300	2	
K-4000	125	6	
	300	4	
	500	4	
K-9000	300	8	
	500	6	
	1000	4	
K-15000	300	10	
	500	4	
	1000	10	

The main structural element of any silo is the frame, made of high-strength steel grades and coated with a zinc layer of 600 g/m². For example, silos of the Rila Ukraine brand use panels made of high-quality Belgian steel ArcelorMittal S 550 GD Z 600, bolted with strength classes 8.8/10.9/12.9. Ladders and sampling devices are installed on the silo body.

In the Poltava region, flat-bottom silos are manufactured at a plant in Lubny. The plant produces universal flat-bottom metal discharge silos (U13–MSVU.PD) with volumes from 356 to 3102 m³. The NSVU.92.xx.V12 model ranges from 356 to 1268 m³, while the MSVU.129.xx.V12 model ranges from 1313 to 3102 m³ [49].

MSVU flat-bottom silos are quickly assembled and equipped with air-duct and forced ventilation systems. The body is made of high-strength steel, the roof withstands snow loads up to 180 kg/m², the base is a reinforced concrete foundation, and the silo is equipped with grain level and temperature monitoring sensors.

Such silos can store from 40 t to 20000 t of grain raw material, allow high-speed loading and unloading, enable active ventilation within the cylindrical container, and provide extensive automation of technological processes. These silos have robust structures and fully comply with European standards.

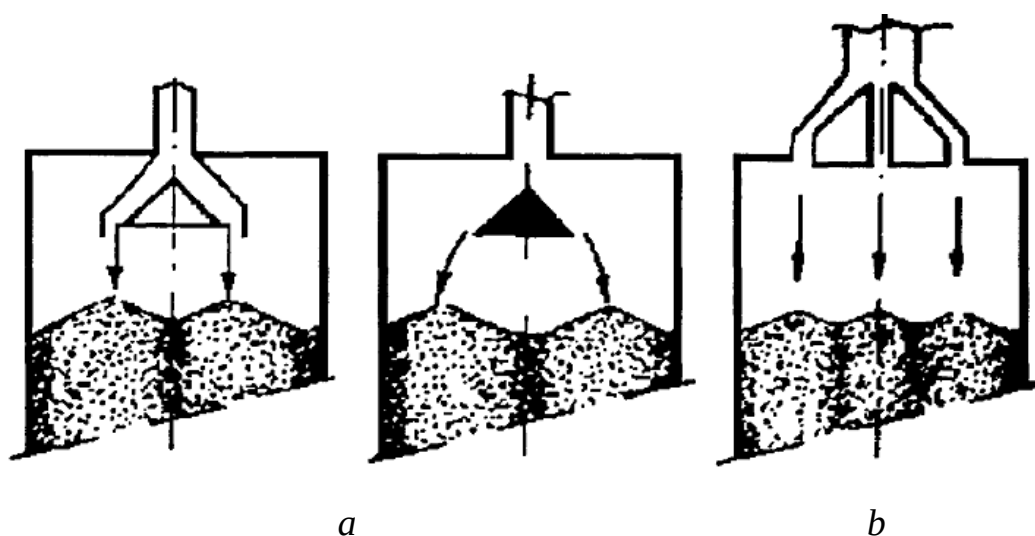
2.3 Methods of Loading Containers with Grain

The most common methods for filling vehicle bodies and cylindrical containers of various purposes with bulk materials include three widely used approaches: jet loading, rain (shower) loading, and cascade loading with the use of a braking effect. Each of these methods has its advantages and disadvantages. The simplest, but not the most effective, is loading by a compact jet (gravity flow). With this method, significant compaction occurs in the lower layers of the grain heap, and segregation is observed.

If a silo is filled by the scattering method, i.e., according to the “rain” or “shower” principle (Fig. 2.5), the grain material is distributed across the cross-section of the silo with a more uniform bulk density. In the case of a dispersed flow (rain loading), a more uniform packing of grain particles is achieved, which increases the container capacity and reduces stratification due to the absence of a central cone pile. As a result, at the

beginning of discharge the pressure on the silo bottom will be partially reduced. In this case, the silo floor does not experience a sudden additional load, and subsequent storage of grain becomes more uniform. One of the optimal ways of filling a container should be considered the one in which the material is distributed as evenly as possible over the container cross-section throughout the loading process—from start to finish.

This method reduces segregation, increases container capacity, decreases compaction of the bulk material, and contributes to longer storage and more stable discharge from the container. It is fairly universal, but is mainly suitable for small-volume containers.



a – filling by scattering; b – filling at several points

Figure 2.5 – Uniform filling of a container and stratification of the bulk material

For gravity loading of grain and milled products without auxiliary devices, i.e., by a compact jet, belt conveyors of various designs are used (Fig. 2.6a). They may be equipped with additional devices (e.g., scrapers) that provide discharge of material from the belt at one or several points. To remove hard and foreign impurities, passive deflectors or pockets with comb-type traps are used (Fig. 2.6a) [50].

Loading by a bucket elevator is also performed by a jet; however, despite high productivity, this device has limited functional capabilities (Fig. 2.6b).

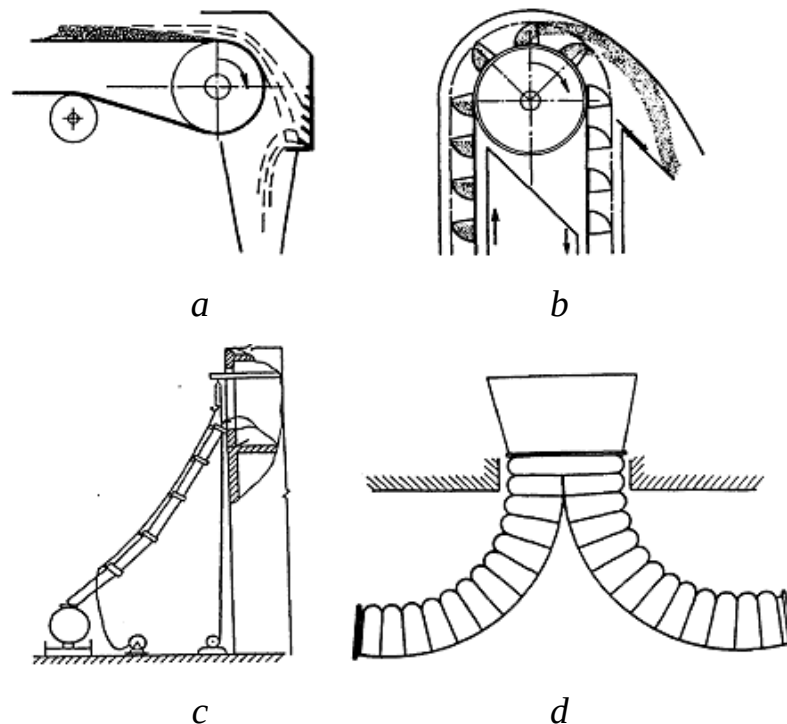
For loading vehicle bodies, a loading spout (loading sleeve) is used (Fig. 2.6c). The spout expands the loading area and reduces product losses when loading into several

containers. It consists of an upper and a lower pipe connected by hinges. A screw conveyor is located inside the upper pipe [50].

A device for loading silo storages and various transport and technological containers is described in [50]. It consists of a loading nozzle, to the lower part of which two outlet pipes with corrugated walls are attached (Fig. 2.6d). This design makes it possible to transport the material in two directions or in one direction.

Using the device shown in Fig. 2.6e, grain can be transported over a long distance: plastic cylindrical pipes connected by clamps with a cable passed through them are arranged vertically or at an inclination. This enables filling, for example, from the top of a bunker, silo, or building [50].

A gravity chute (Fig. 2.6f) includes a complex corrugated spout. It has a closing gate and a drive. When material enters the spout, it stretches as the load increases. Upon reaching the container bottom, the gate opens due to contact, and raising the spout ensures unloading. Due to the small drop height, destruction of grain particles is prevented [50].



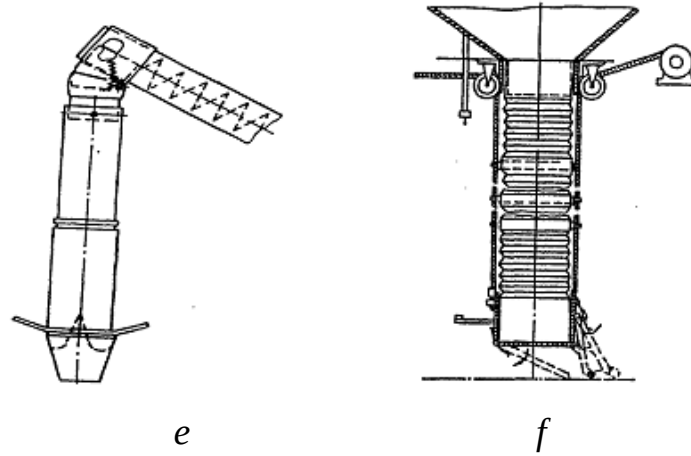
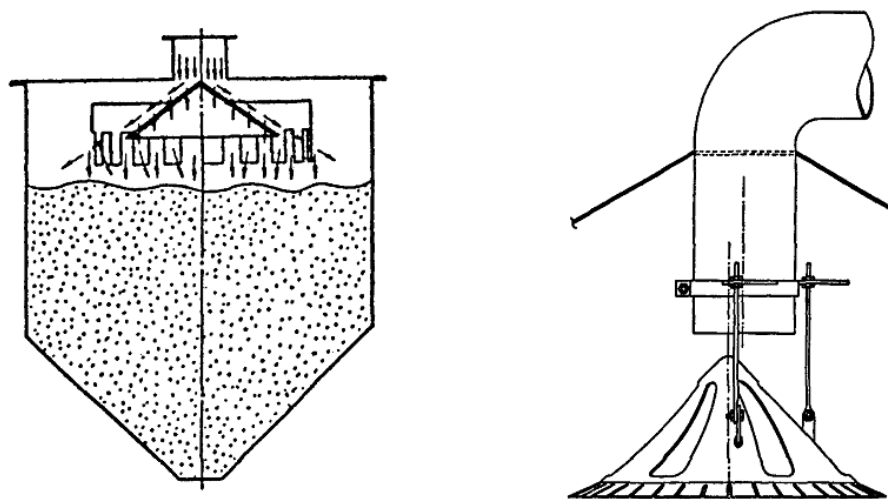


Figure 2.6 – Loading devices with a concentrated flow

To reduce grain damage during loading into silos, special loading devices are used [50]. Their working elements may include various cones, transfer shelves installed in a telescopic pipe, concentric rings with vertically arranged blades, vertical screw conveyors with openings, fixed chutes with a braking effect, and others.

2.4 Description of Loading–Distributing Device Designs

Paper [51] considers devices installed inside silos and intended to reduce the falling speed of grain material from significant heights. Figure 2.7 shows two conical distributors installed under the silo inlet. In such devices, grain from the inlet hits the side surface of the cones, causing the vertical velocity component to change into a velocity directed at an angle to the horizon. As a result, the grain is damaged less, and the formed heap exhibits lower dynamic compaction and segregation.



*a**b*

Figure 2.7 – Conical distributors

The device (Fig. 2.7a) for distributing bulk material includes a cone with openings and a slotted ring (casing) concentrically installed with a clearance around the cone base. While moving over the cone, the grain is uniformly distributed over its surface; part of it passes through the openings and falls into the container, while another part, reaching the cone base, is directed toward the bunker periphery [53].

The loading device (Fig. 2.7b) consists of a loading nozzle and a splitting cone fixed to it using a clamp and supports. The cone has longitudinal vertical cutouts. During grain supply, kernels contacting the cone surface change their direction and are distributed over a large radius. The cutouts ensure part of the flow falls into the central zone of the container [50].

When loading silos using conical distributors, a relatively uniform distribution of grain without formation of a central cone pile is observed, which reduces dynamic loading and segregation; however, grain damage still occurs.

Mechanical loading–distributing devices (centrifugal disc and rotary spreaders) have also become widespread. However, devices with hydraulic drives have not been widely adopted due to difficulties in manufacturing and operation.

A fixed loading device is shown in Fig. 2.8a. It reduces the density of the grain flow falling downward. It consists of a conical bunker with an expanding chute fixed inside it. Grids with cells are mounted on the inner walls of the chute to reduce grain speed. The cell sizes differ: the upper cells are larger than the lower ones, and within each grid the cell sizes increase from the center toward the periphery. As grain passes through the grid openings, its speed decreases, which reduces grain damage and provides uniform distribution across the entire container area [54].

Figure 2.8b presents a device consisting of a distributing bunker with three rows of rectangular openings on its side surface, arranged in a checkerboard pattern. Outside the bunker bottom, a vertical shaft is mounted with the possibility of rotation; two rows of blades are fixed on the shaft at preset angles in horizontal and vertical planes [50].

When material hits the blades, it rotates the shaft, ensuring uniform scattering around the container perimeter.

For loading stationary and mobile containers, a device with a rotating disc on a vertical shaft and a ring limiter is used (Fig. 2.8c). The limiter can reciprocate along the shaft and rotate around it; it also has discharge windows on the side wall. Increasing the useful scattering volume is achieved by changing the disc rotational speed [50].

Other centrifugal spreaders exist (Fig. 2.8d), in which concentric rings with vertically mounted blades are fixed horizontally on a vertical shaft [55]. The bulk material is supplied while the device rotates. Grain reaching the ring surface is thrown by the blades to distances corresponding to each ring diameter, which provides uniform distribution within the silo.

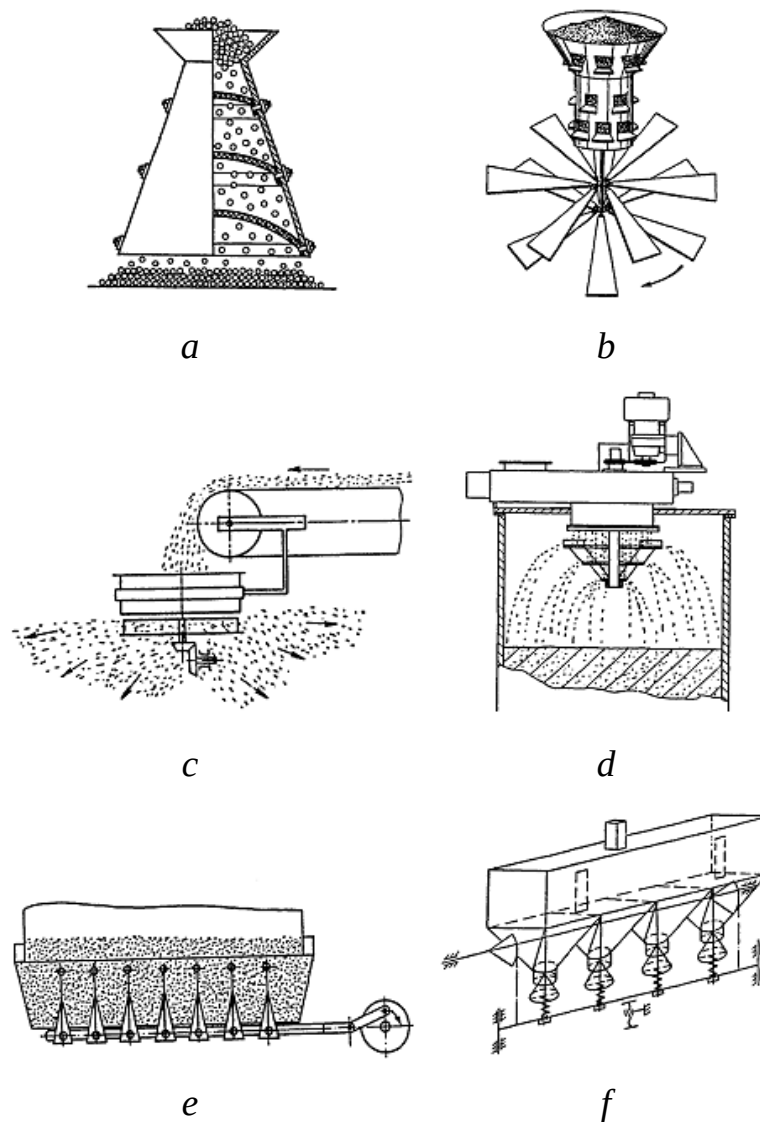
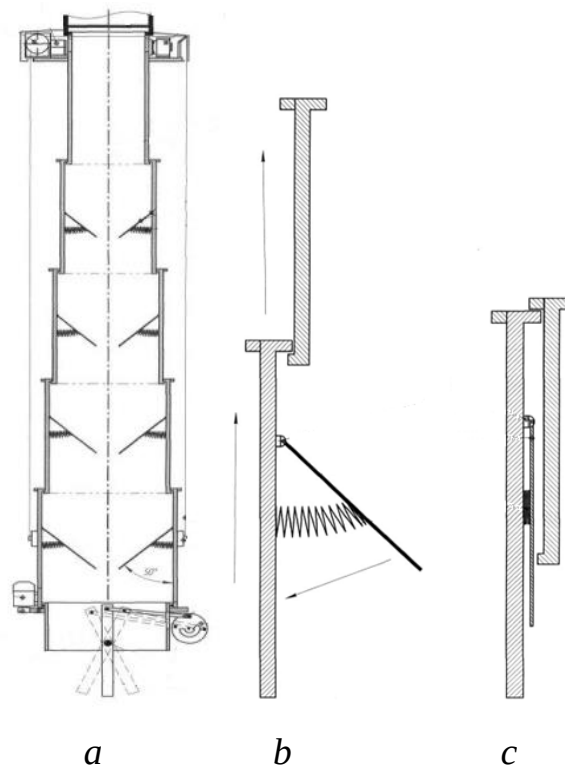


Figure 2.8 – Loading devices with a dispersed flow [50]

A bunker with a movable frame carrying uniformly arranged vertical blades (Fig. 2.8e) can be used for loading vehicles. The blades, due to hinged mounting, can open and close the discharge outlets. During material supply, a reciprocating drive of a fork-shaped frame is activated; oscillating blades provide uniform distribution in the receiving container [50].

The device shown in Fig. 2.8f includes a bunker with discharge funnels and outlets covered by cones, and is intended for loading grain and processed products [50]. Under the material weight, cone valves move downward, forming annular gaps at the perimeter of outlets; however, this design is complex to manufacture.

A way to solve the problem of impact-free silo loading is the use of various cascade devices that reduce the free-fall height of grain onto the container bottom. The cascade method provides more uniform distribution over the silo perimeter, reducing segregation, compaction, and kernel damage. Figure 2.9 shows a telescopic pipe with lateral transfer shelves used for gentle loading by the cascading principle.



a – longitudinal section along the vertical axis; b – side blades in the open position; c – side blades in the folded position

Figure 2.9 – Device for uniform grain loading into a silo

When using telescopic pipes, grain transfers from one shelf to another, and its velocity continuously changes both in magnitude and direction. The device consists of a vertical telescopic pipe made of N cylinders, inside which spring-loaded transfer blades are installed. It is equipped with a vibrator to prevent bridging and a winch for raising and lowering the cylinders.

The telescopic pipe is automatically lowered to the silo bottom (without touching it). Grain moves inside the pipe by transferring from one blade to another. The blades slow the grain, reducing its linear velocity and free-fall distance, thus significantly decreasing damage [56].

A disadvantage of this device is the high metal consumption of the telescopic pipe, which increases the load on the silo structure, and the possibility of grain abrasion due to mutual friction during movement inside the pipe.

To reduce the speed (and thus damage) of granular materials during loading, a cable with a row of damping elements mounted across it can be used (Fig. 2.10a). Their radial size is smaller than the container diameter. As the container fills, the cable is pulled upward, preventing obstruction during discharge [50].

For transferring bulk and lump materials using belt conveyors, a gravity chute is used (Fig. 2.10b). It is a zigzag chute with a curved bottom. Pockets located opposite the outlets of each step brake the flow. As a result, the speed of the coarse fraction is periodically reduced, while fine particles move continuously.

A cascade device (Fig. 2.10c) consists of inclined pipes connected by elbows that change the flow direction, thereby reducing speed on these sections [50]. Discharge from cascade chutes occurs through windows in their upper part. Even spacing of outlets allows staged loading with a fall height from 0 to 1.5 m. A disadvantage is that the device remains inside after loading, which can promote bridging and hinder discharge.

To increase mechanization for fragile materials, a device including a bunker and a variable-length loading chute can be used (Fig. 2.10d). Inclined shelves are mounted inside in a checkerboard pattern, and drums are installed on the bunker body with belts that form the loading chute. As belts unwind, they form a tube lowered into the vehicle body or other container and fixed by clamps. As the container fills, belt length decreases, reducing fall height inside the chute and at its outlet [57].

The device shown in Fig. 2.10e is suitable for loading root crops. The material falling from the conveyor rolls along semicylindrical guides due to gravity and inertia, with an initial velocity having only a vertical component.

Loading silos and other cylindrical structures with grain or meal pellets can also be performed using vertical gravity–cascade conveyors employing conical distributors.

The device shown in Fig. 2.11 consists of a vertical conveying channel formed by a series of truncated cones arranged one under another and rotated relative to each other. A clearance is provided between adjacent cones; each upper cone is oriented opposite to the adjacent lower cone and rotated by 180° about the vertical axis [58].

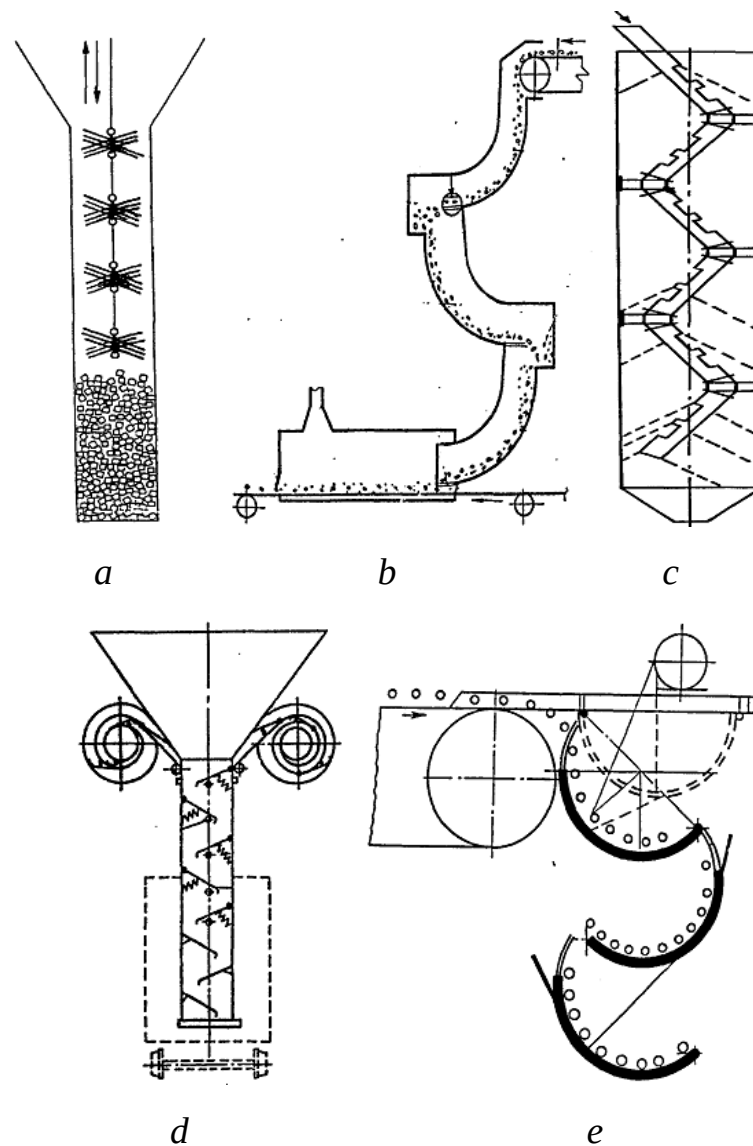


Figure 2.10 – Loading devices with cascade chutes [50]

Operation is as follows: grain from an overhead conveyor enters the inlet and falls onto the inner surface of the first truncated cone. Upon contact, a conditionally elastic impact occurs, and part of the kinetic energy is lost due to impact and friction, causing a reduction in speed and a change in direction. The grain then moves to the next cone, and the process repeats. Figure 2.12 illustrates the grain movement along truncated cone surfaces.

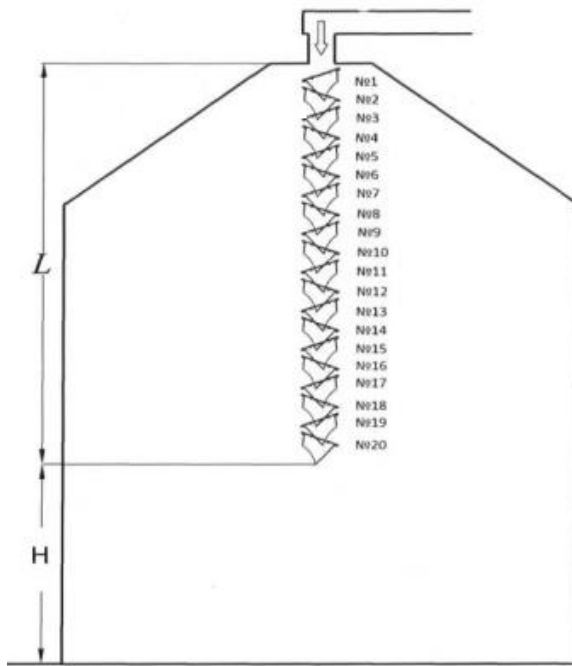


Figure 2.11 – Vertical gravity–cascade conveyor

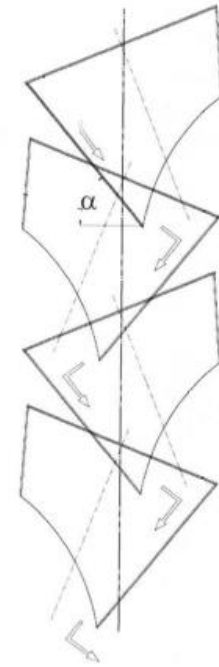


Figure 2.12 – Grain movement along the internal surfaces of truncated cones

Parameter H (Fig. 2.11) defines the height from which grain can freely fall onto the silo bottom or the grain heap without significant damage. For different crops, H may vary from 1 to 5 m.

Another gravity–cascade device is shown in Fig. 2.13. It consists of a vertical conveying channel formed by transfer cones. The transfer element is made as a disc with a rim. The disc surface is the working surface: the central part is conical, and the peripheral part (between cone and rim) contains sector-shaped transfer shelves alternating with through openings. The conical surface ensures centering of adjacent discs and the necessary clearance during assembly [59]. The cascade arrangement allows the use of gravity for grain loading.

During operation, grain enters the transfer shelves of the first disc. Collision with the shelves produces a conditionally elastic impact and changes the direction of movement, thereby reducing velocity in the vertical conveyor.

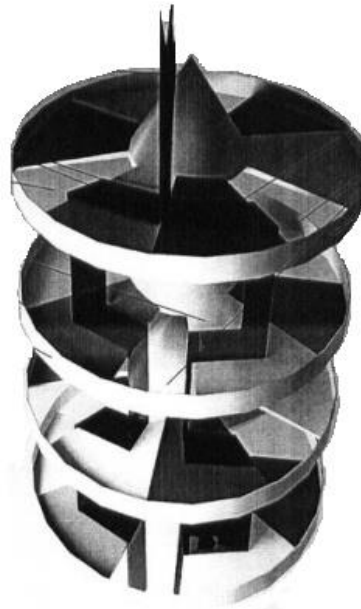


Figure 2.13 – Gravity–cascade conveyor with conical discs

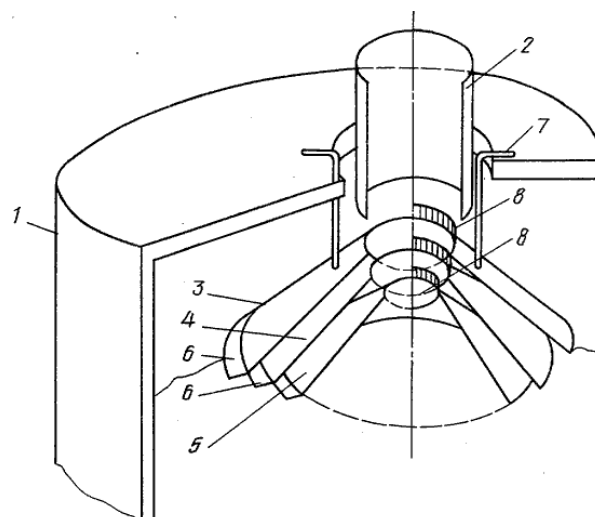
During loading of silos with grain for long-term storage, a dust–air mixture forms. To reduce dust emissions, foreign companies developed the continuous loading system Vortex [60]. It consists of a vertically movable sleeve with a series of truncated transfer cones arranged sequentially inside it. The cone shape reduces grain flow velocity and promotes “mass flow.” Figure 2.14 shows the movement of grain and dust–air mixture in the Vortex system. This system reduces dust emissions to a minimum level of about 5 mg/m^3 .



Figure 2.14 – Vortex-type loading system

The Vortex system is mainly used to reduce dust emissions during handling operations. The sleeve retains dust, but grain still falls to the silo bottom, so grain integrity is not fully ensured.

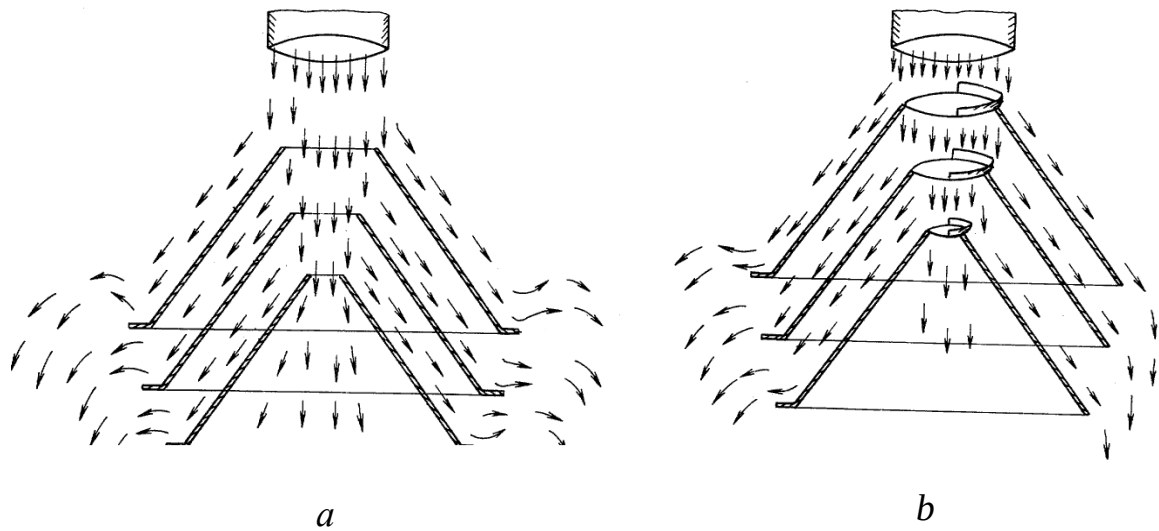
For uniform loading of silos, inventors S.V. Novoselov and A.D. Donin proposed the gravity loading device shown in Fig. 2.15. It consists of a vertically installed cylindrical housing (1), an inlet nozzle (2), and coaxial cones (3, 4, 5) arranged one below another, with horizontal canopies (6) and casings (8) [61]. The device is installed inside the silo along the axis of the inlet.



1 – housing; 2 – inlet nozzle; 3, 4, 5 – coaxial cones; 6 – horizontal canopies;
7 – fasteners; 8 – casings

Figure 2.15 – Device for uniform loading of bulk materials

When grain is fed, most passes through the opening of the upper cone, while part slides along the cone surface to the canopy. The canopy changes the flow direction and directs grain closer to the silo wall (Fig. 2.16). Grain passing through the upper cone opening enters the middle cone opening; part is directed into the annular space between the cones and discharged downward. The remaining grain passes through the lower cone and falls into the central part of the silo.



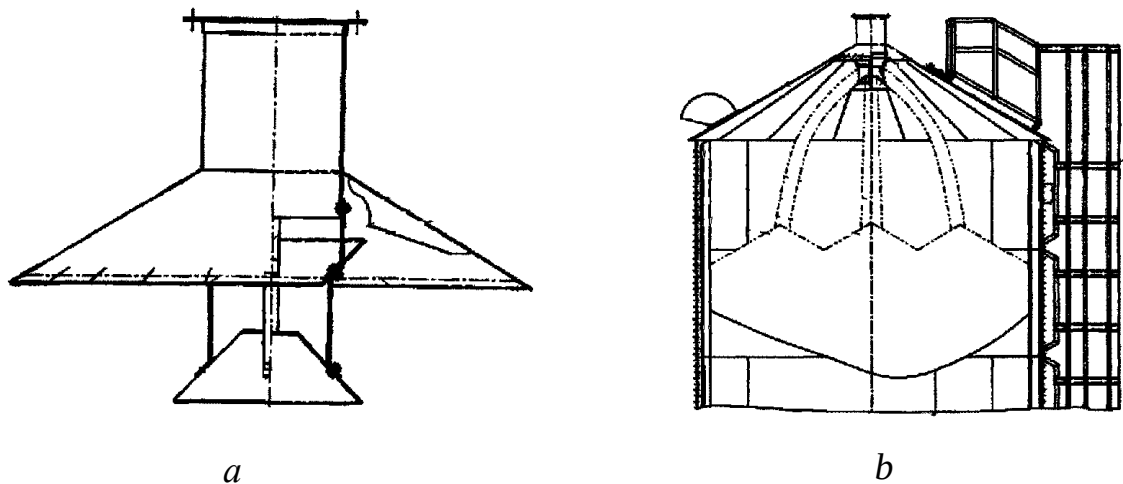
a – symmetric position of the inlet nozzle; b – asymmetric position of the inlet nozzle

Figure 2.16 – Grain flow in a conical-type loading device

A corrugated chute is sometimes used for loading: it can extend as the container fills. Upon reaching the bottom, a lower gate opens and lifting the chute releases the material. Due to a small fall height, kernel damage is minimized.

Figure 2.17a shows a device intended for uniform and homogeneous loading of silos with bulk material. It includes a loading nozzle mounted on the silo roof and a downward-directed conical casing with a smaller lower opening suspended coaxially under the nozzle.

Figure 2.17b illustrates silo loading: grain fed into the nozzle passes through the casing opening, hits the casing surface, and splits into two flows—one toward the center through the smaller opening, and another along the outer conical surface toward the periphery. Formation of a central mound and a peripheral ring mound, as well as mixing of fractions, improves uniform distribution inside the silo and reduces bending loads on the shell structure. A disadvantage is inefficient use of gravitational energy during distribution and continued grain damage due to a large falling distance.



a – loading device; b – schematic diagram of loading a silo with bulk material

Figure 2.17 – Device for loading a silo or a similar cylindrical shell-type container with bulk material

The conical shell is installed with a clearance between the lower part of the vertical cylindrical loading spout and its upper edge. Beneath the conical shell, a second conical shell with a smaller end opening directed upward is coaxially mounted using brackets. The area of the smaller end opening directed upward is twice smaller than the area of the smaller end outlet opening directed downward of the shell, which in turn is smaller than the area of the opening of the loading spout [62].

Figure 2.17b shows a schematic diagram of loading a silo with grain. The grain flow supplied from above into the loading spout passes through the outlet opening of the loading spout and the outlet opening of the shell, reaches the shell, and is divided into two streams. The grain flow that passes through the smaller end opening of the shell is

discharged toward the center of the silo, while the flow that moves along the outer conical surface of the shell is evenly directed toward the periphery of the silo.

The formation of a central mound in the middle part and an annular mound closer to the periphery, as well as the mixing of fractions in the loading device, contribute to a more uniform distribution of grain within the internal volume of the silo. This ensures a reduction in bending stresses acting on the shell structure.

The disadvantage of this device is the inefficient use of the energy of the gravitational force flow during the distribution of the grain mass over the working area of the silo, as well as grain damage caused by its fall from a considerable height to the bottom of the silo.

Figure 2.18 shows a device [50] in which grain is first gravity-fed to the top of the heap and onto a driven cone with vertical partitions, after which the cone drive is switched on. The partitions capture the incoming material and, due to centrifugal forces, throw it toward the periphery, filling voids.

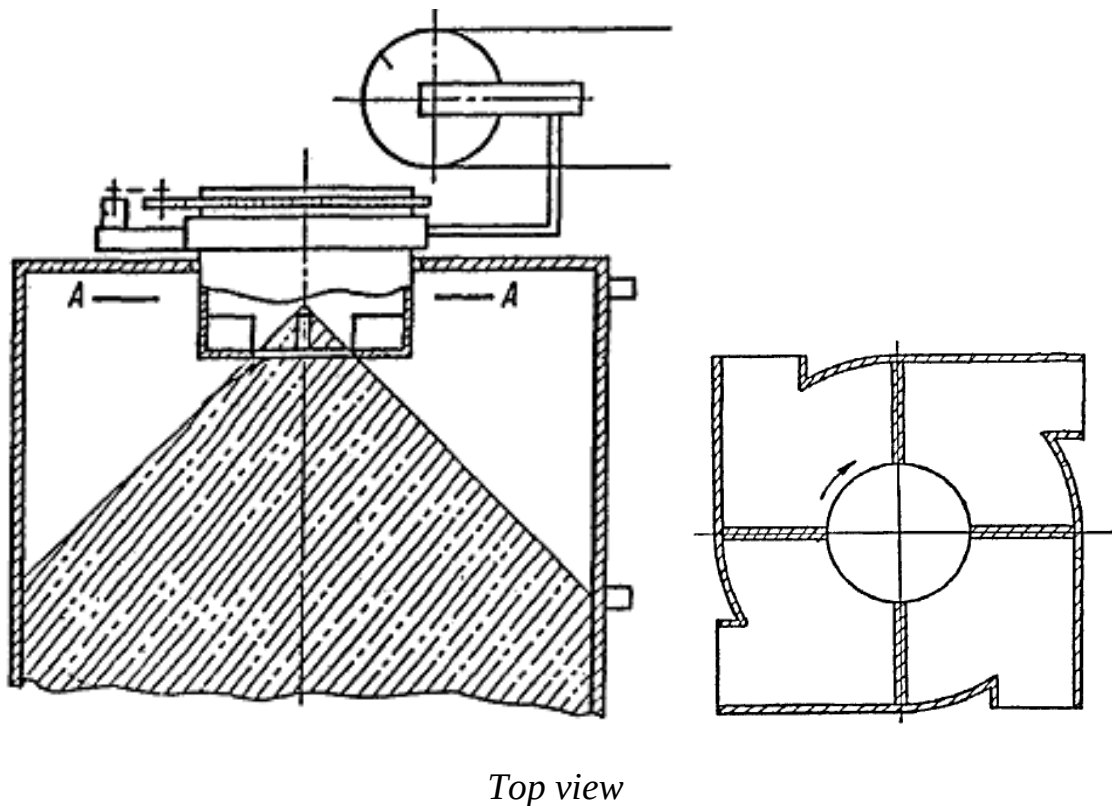


Figure 2.18 – Combined loading device

Driven loading devices are widely used (centrifugal, disc, rotary spreaders, etc.).

For stationary and mobile containers, device [63] includes discs on a vertical shaft with annular perforated limiters (Fig. 2.19a). During rotation, the bulk mass is accelerated by centrifugal force and discharged through the perforations. By changing disc size and speed, different distribution patterns are achieved.

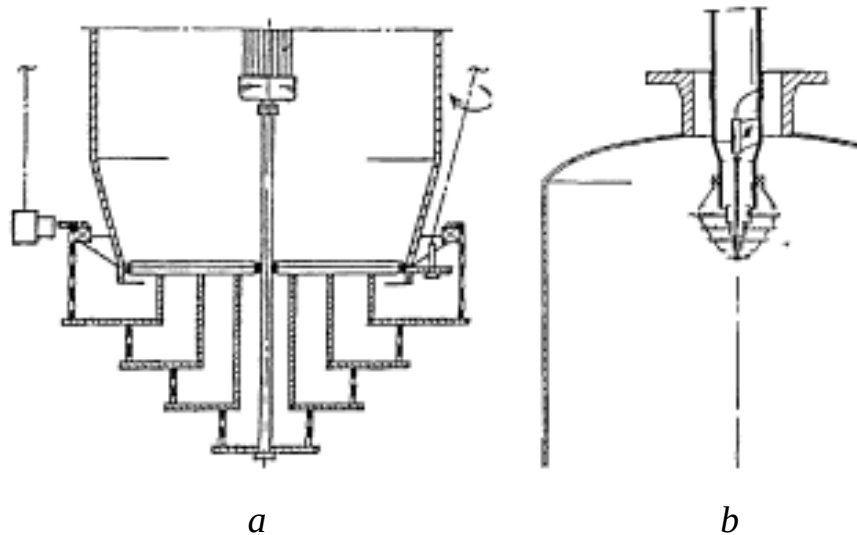


Figure 2.19 – Schemes of driven loading–distributing devices

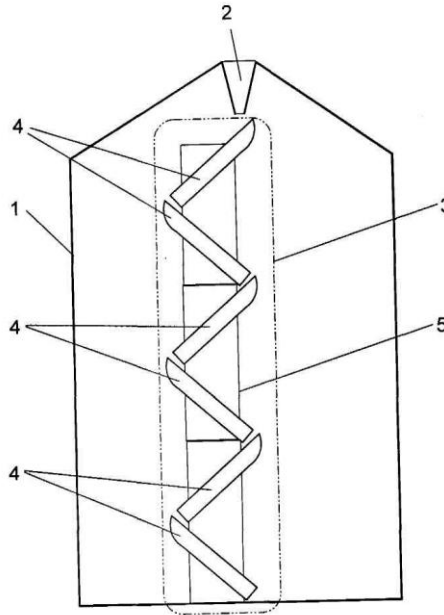
Figure 2.19b shows a centrifugal spreader with discs and vertical blades. The material is fed while the device rotates; blades throw grain to distances corresponding to ring diameters, ensuring uniform distribution.

Classical studies have shown that drop height and surface type significantly affect grain integrity. The highest damage occurs when grain freely falls from heights greater than 12–15 m [64] onto a hard surface or onto a grain layer. Foreign authors compared standard gravity loading with stepped speed dampers; such devices reduced broken kernels by 30–50% [136]. Proposed solutions include shelf cascades (“ladders”), spiral chutes, and clamping valves regulating flow density. However, such designs work only with free-flowing materials; cohesive particles may clog openings.

A fixed internal cascade-loading device is shown in Fig. 2.20. It is made as multiple inclined trays that act as speed dampers. The device consists of a container (1), an inlet nozzle (2), a fall-speed damper (3), inclined trays (4), and a frame (5) [65]. The trays are connected so that the outlet of a preceding tray feeds the inlet of the next one.

The tray inclination angle can be adjusted between 25° and 40° relative to the horizontal plane.

Operation is as follows: grain gravity-feeds onto the first tray. The flow speed is reduced at the tray outlet (which is narrower than its inlet). When transferring from one tray to the next, the flow direction reverses, providing additional braking.



1 – cylindrical container; 2 – inlet nozzle; 3 – grain fall dampers; 4 – inclined trays; 5 – metal frame

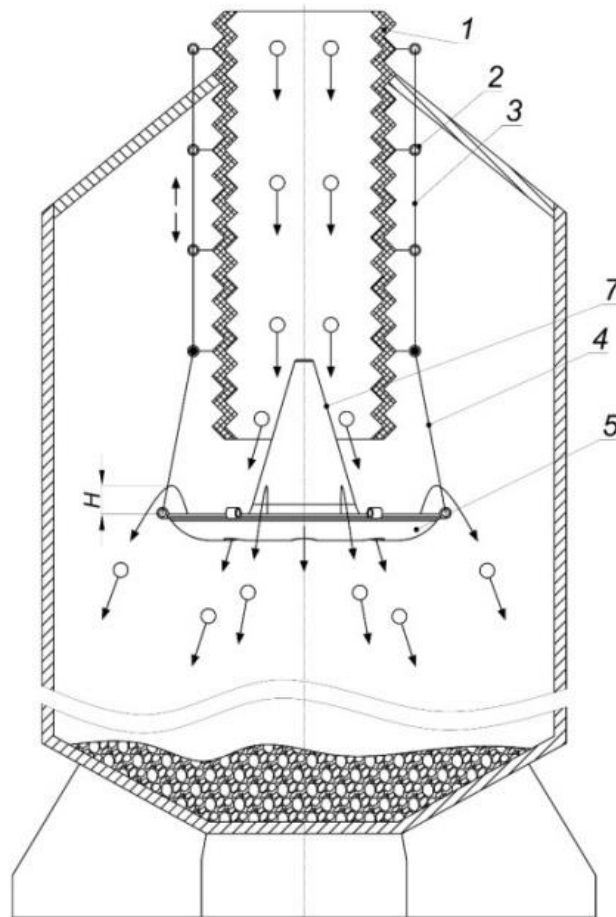
Figure 2.20 – Fadeyev grain storage facility

Adjusting tray angles allows matching them to the friction angle of the grain mass being loaded. During filling, the trays become buried in grain within the loaded volume. Such loading neutralizes segregation, preserves seed integrity, and reduces compaction in the lower heap layers.

2.5 Loading Devices for Metal Silos with a Braking Effect

To improve the process of loading silos with grain material without causing damage to it, devices are used that, despite certain costs, generally enhance the functional parameters of the storage unit.

Loading devices are technical means intended for careful filling of a container with bulk material. Figure 2.21 shows a device for gentle loading of grain cargo into a silo [66].



1 – corrugated sleeve; 2 – guide rings; 3 – cable; 4 – fasteners; 5 – toroidal plate; 6 – curved edges; 7 – truncated cone

Figure 2.21 – Device for gentle loading of grain into a silo

The device for gentle loading of grain into a silo consists of a corrugated loading sleeve 1, which has external guides in the form of rings 2 with cables 3 threaded through them; a mechanical drive (not shown) for raising and lowering the sleeve; and a toroidal plate 5 attached by flexible links 4 to the sleeve guides 1. The plate has outward-curved edges 6, a central conical guide 7 oriented with its smaller base toward the inner space of the sleeve 1, and a circular array of through-holes 8 in the bottom 9 of the plate 5.

The device operates as follows. When it is necessary to fill an emptied silo with grain, the corrugated sleeve 1 is extended along its entire length by the raising–lowering

mechanism, lowering it together with the toroidal plate 5 to the bottom of the silo. After the sleeve 1 has been fully extended, the grain mass is fed into its upper part and, under the influence of gravity, moves toward the silo bottom. Upon reaching the smaller base of the central conical guide 7 of the toroidal plate 5, the grain is distributed and moves through the annular gap between the guide 7 and the inner surface of the sleeve 1. The annular gap continuously decreases as the grain approaches the larger base of the conical guide 7, which makes it possible to form an annular grain stream of small cross-sectional area.

After reaching the toroidal plate 5, the grain contacts the concave surface of its bottom 9 and, due to inertia and sliding along this surface, is thrown upward from the plate 5 to a certain height H , thereby dissipating excess kinetic energy. Otherwise, this energy, upon impact with the silo bottom, would cause grain damage and loss of integrity. The curved edges 6 of the plate 5 improve the grain ejection without creating additional resistance. Part of the grain that does not have sufficient velocity to leave the plate 5 tangentially to its inner surface falls downward through the array of holes 8 in the bottom 9 of the plate 5. The discharge velocity through the holes 8 is significantly reduced due to repeated contact interactions between grains within the flow and with the surface of the bottom 9, which also helps reduce the impact force of the grain on the silo bottom.

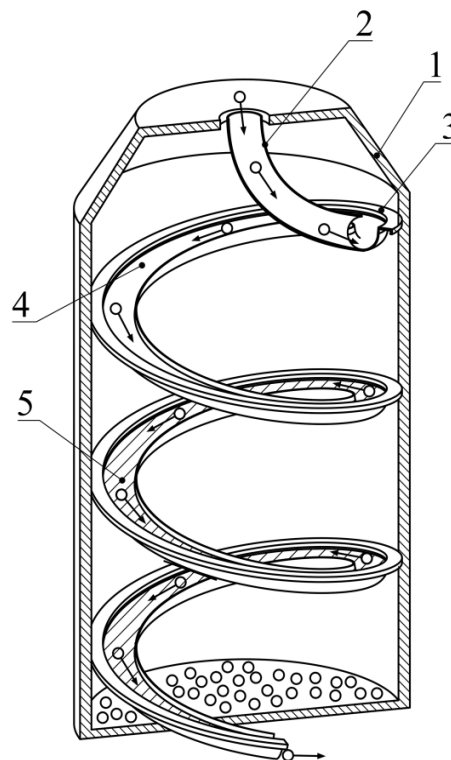
The discharge of the grain flow from the plate 5 along different paths makes it possible to increase the cross-sectional area of the grain stream moving downward inside the silo, ensuring more uniform filling of its lower part.

As the silo is gradually filled, the height of the grain layer increases and approaches the toroidal plate 5. The plate 5, together with the corrugated sleeve 1, is raised upward by the lifting mechanism, maintaining a gentle loading process at a higher level above the bottom.

Thus, the use of a toroidal plate with a central conical guide and a circular array of through-holes in its bottom in the gentle loading device helps reduce the kinetic energy of grain motion, minimizing possible deformation and breakage and reducing the degree of damage. It also increases the cross-sectional area of the grain stream and distributes it uniformly over the filling surface.

The use of braking devices made in the form of a helical spiral for loading tall cylindrical silos makes it possible to deliver grain to the bottom of the container without damage or segregation. Figure 2.21 shows a schematic diagram of a cylindrical silo with a spiral loader [67].

The silo includes a cylindrical storage bin 1 for grain; in its upper part a tubular loading spout 2 is fixed. On the inner side of the cylindrical bin 1, a peripheral open helical channel 3 is fixed by brackets 4. The loading spout 2 directs the grain flow from the upper part of bin 1 into the internal space of channel 3.



1 – cylindrical bin; 2 – loading spout; 3 – open helical channel; 4 – acceleration section of the helical channel; 5 – braking section of the helical channel

Figure 2.21 – Silo with a spiral loader

The body of the helical channel 3 is formed by twisting a U-shaped profile along a helix with a variable pitch that decreases sequentially from the greatest value h_3 on section L3 of the helix in the upper part of bin 1 to the smallest value h_1 on section L1 in the lower part of bin 1. This makes it possible to obtain smoothly connected sections of channel 3 with a gradual reduction of the descent angle along the height of bin 1 from the greatest φ_3 to the smallest φ_1 . The angle φ_1 is selected slightly greater than the

friction angle of the grain crop stored in the silo and is taken within 30–40 degrees. The values of angles ϕ_2 and ϕ_3 are taken 10% and 20% greater than ϕ_1 , respectively.

The silo operates as follows. Grain flows by gravity from the loading spout 2 to the inlet of the helical channel 3. In the upper part, the grain stream gains a significant increase in velocity due to the large descent angle ϕ_3 . This is necessary to prevent grain stagnation and to avoid overflow of grain over the channel edges 3, which could lead to uncontrolled free fall into the lower part of bin 1 and a high likelihood of mechanical deformation. After passing the steep section of the helical channel of length L_3 , the grain velocity begins to decrease gradually due to the smaller descent angle ϕ_2 on the next section L_2 . Upon reaching the final descent section L_1 , the grain stream smoothly pours into the lower part of the bin, filling its volume. On this section, due to the smaller angle ϕ_1 , the grain exit velocity from channel 3 is reduced to a level that prevents critical impact forces on the walls or bottom of bin 1, thereby reducing the probability of mechanical damage. As bin 1 is filled, the helical channel 3 is also covered with grain.

Thus, the use of a screw-shaped channel in the silo contributes to creating the required velocity gradient of the grain stream along the entire channel length, ensuring unobstructed and fast grain movement in the upper part, while deceleration at the outlet minimizes possible deformation and reduces the level of grain damage.

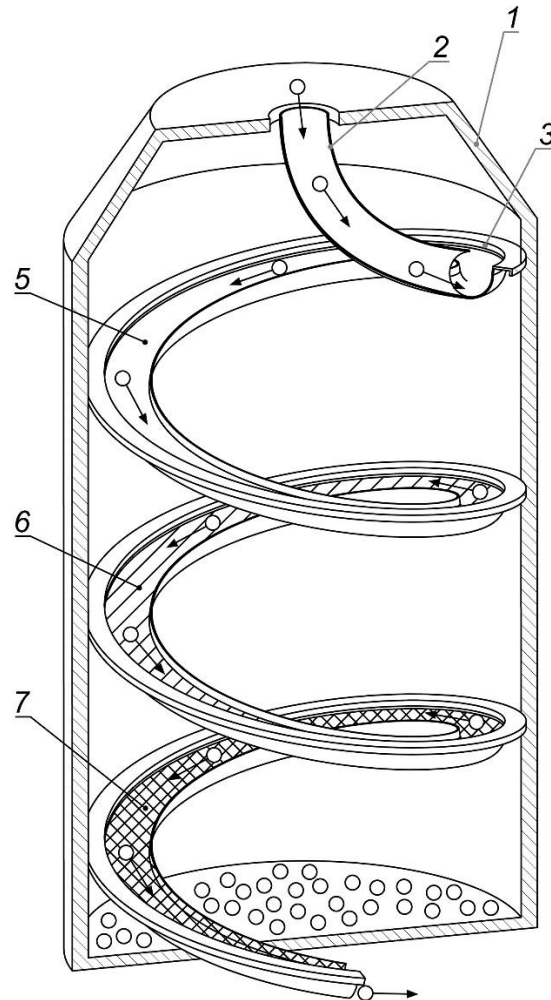
Figure 2.22 shows a silo equipped with a spiral loader whose working surface is coated with materials having different adhesion levels [68].

The silo includes a cylindrical storage bin 1 for grain, with a tubular loading spout 2 fixed in its upper part. On the inner side of bin 1, a peripheral open helical channel 3 is fixed by brackets 4. The loading spout 2 directs the grain flow from the upper part of bin 1 into the internal space of channel 3.

The body of the helical channel 3 is formed by twisting a U-shaped profile along a helix. The resulting descent surface is divided into three equal sections 5, 6, and 7. Each section is coated with materials having different tribological properties, and for each lower section of the descent surface, the level of contact interaction with the grain increases.

The silo operates as follows. Grain flows by gravity from the loading spout 2 into the helical channel 3. In the upper part, on the first section 5 with minimal contact

properties, the grain stream gains a significant increase in velocity. This is required to prevent stagnation and overflow of grain over the channel edges 3, which could cause uncontrolled falling into the lower part of bin 1 and a high probability of mechanical deformation.



1 – cylindrical bin; 2 – loading spout; 3 – open helical channel; 4 – acceleration section covered with coatings of different tribological properties; 5 – braking section covered with coatings of different tribological properties

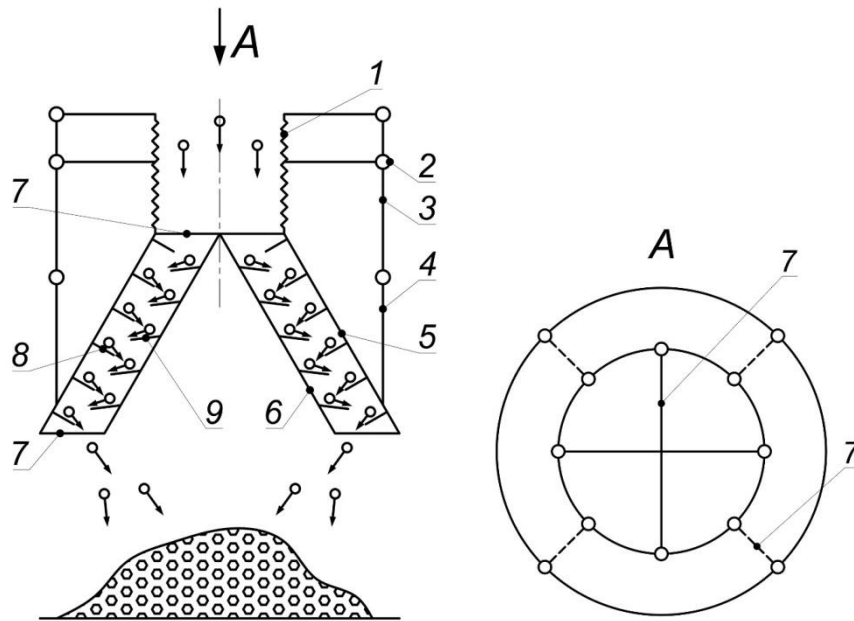
Figure 2.22 – Silo with a spiral loader and a non-uniform descent-surface coating

After passing the first section 5, the grain enters the second section 6, where due to the different tribological coating the contact interaction increases. This enhances the braking effect by increasing friction and slowing the rate of velocity growth of the grain mass in the helical channel 3. On the last section 7, grain motion occurs with a decaying change in velocity due to the highest-contact coating, which prevents critical impact

forces on the walls or bottom of bin 1 and reduces the probability of mechanical damage. As bin 1 is filled, the helical channel 3 is also covered.

Thus, the use of a screw-shaped channel with separately designated sections having coatings of different tribological properties makes it possible to create the required velocity gradient of the grain stream along the entire channel length. This ensures unobstructed and fast motion in the upper part and, due to deceleration at the outlet, minimizes possible deformation and reduces grain damage. In this case, when creating the helical channel inside the silo, it is sufficient to maintain a constant descent pitch, which does not require significant labor costs during installation.

A conical-type loading device (Fig. 2.23) can be used to reduce grain damage and segregation during filling and to increase filling uniformity [69].



1 – corrugated sleeve; 2 – guide rings; 3 – cable; 4 – guide links; 5 – outer cone;
6 – inner cone; 7 – cross-members

Figure 2.23 – Conical-type loading device

The conical-type loading device consists of a corrugated loading sleeve 1 with external guides in the form of rings 2, with cables 3 threaded through them; a drive mechanism (not shown) for raising and lowering the sleeve; and an outer cone 5 truncated at the top, attached by flexible links 4 to the sleeve guides 1. Inside it, symmetrically, there is a complete cone 6, fixed at the top and bottom by cross-members

7 to the outer truncated cone 5. The inner side surface of the outer truncated cone 5 is equipped with a series of conical discs 8 arranged perpendicular to the side surface of this cone and at an angle α to the horizon. The outer side surface of the complete cone 6 is equipped with conical discs 9 arranged at an angle β to the horizon. The conical discs are arranged in the space between the inner side surface of the truncated cone 5 and the outer side surface of the complete cone 6 with a shifted pitch, and the discs mounted on the outer surface of cone 6 are always located between two adjacent conical discs of the truncated cone.

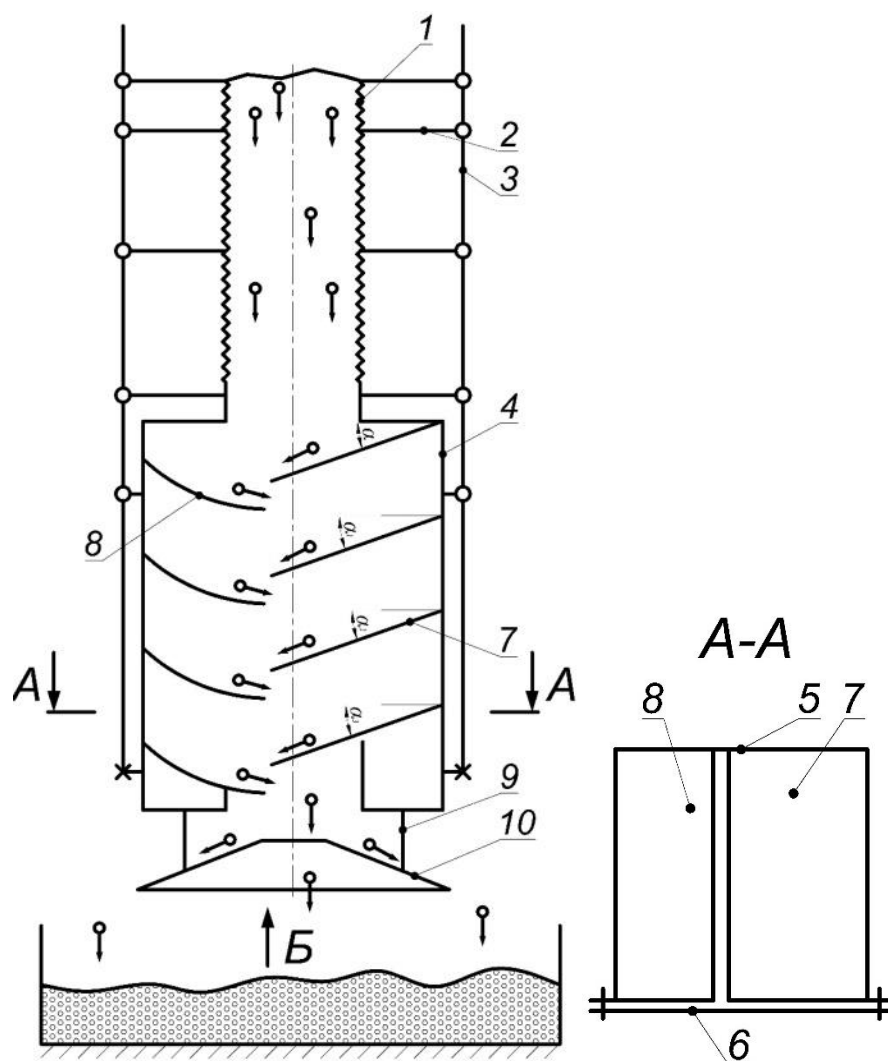
The conical-type loading device operates as follows. When it is necessary to load an empty silo with grain, the corrugated sleeve 1 is extended by the raising–lowering mechanism along its entire length together with the conical device to the bottom of the silo. After the sleeve 1 is fully extended, grain material is fed into its upper part and, under the influence of gravity, moves toward the concrete bottom of the silo. Upon reaching the apex of the inner cone 6, the grain experiences a conditionally elastic impact and changes its direction of motion from vertical to inclined. Due to this change, the grain reaches the first conical disc 8 on the inner side surface of the truncated cone 5. In the zone of conical discs 8 and 9, the grain continuously changes its direction of motion and its movement along the disc surfaces slows down, significantly reducing the impact force on the concrete base of the silo.

Thus, the use of conical discs in the loading device helps reduce the kinetic energy of grain motion, minimizing possible deformation and destruction and decreasing grain damage. The use of simple geometric structural elements simplifies manufacturing and installation.

In industrial practice, when filling silos with grain material, an overflow-type loading device may be used [70]. Figure 2.24 shows a schematic diagram of this device.

The overflow-type loading device consists of a corrugated sleeve 1 with external guides in the form of rings 2 and cables 3 threaded through them; a drive mechanism (not shown) for raising and lowering the sleeve 1; and a cable 3 rigidly fixed in the lower part of the rectangular box 4. The rectangular box 4 consists of a U-shaped part 5 to which a rectangular plate 6 is attached. Inside the box 4, on the right side, overflow shelves 7 with straight inclined surfaces are installed at a certain angle to the horizon,

with $\alpha > \alpha_1 > \dots > \alpha_n$. On the left inner side of the box 4, overflow shelves 8 with curvilinear inclined surfaces are installed. In the lower part, a truncated conical spreader 10 is fixed by pins 9.



1 – corrugated sleeve; 2 – guide rings; 3 – cable; 4 – rectangular chute; 5 – U-shaped chute section; 6 – plate; 7 – overflow shelves with a straight inclined surface; 8 – overflow shelves with a curvilinear inclined surface; 9 – vertical pins; 10 – truncated cone

Figure 2.24 – Overflow-type loading device

The device operates as follows. To load an empty silo with grain, the sleeve 1 is extended by the lifting mechanism along its entire length together with the overflow device 4 to the bottom of the silo. After the sleeve 1 is fully extended, grain material is fed into its upper part and moves under gravity toward the concrete base. Upon reaching

the first overflow shelf 7, the grain changes its vertical velocity vector to a vector directed toward the second curvilinear shelf 8. Further movement proceeds similarly. The path length increases depending on the number of shelves installed in the box. While moving through the overflow device, the grain velocity continuously changes in magnitude and direction; therefore, at the outlet the grain velocity is small and grain damage does not occur. After leaving the overflow device, the grain falls onto the side surface of the truncated cone 10. Part of the grain rolls around the entire perimeter of the silo, while another part falls through the central opening of cone 10 into the middle of the silo.

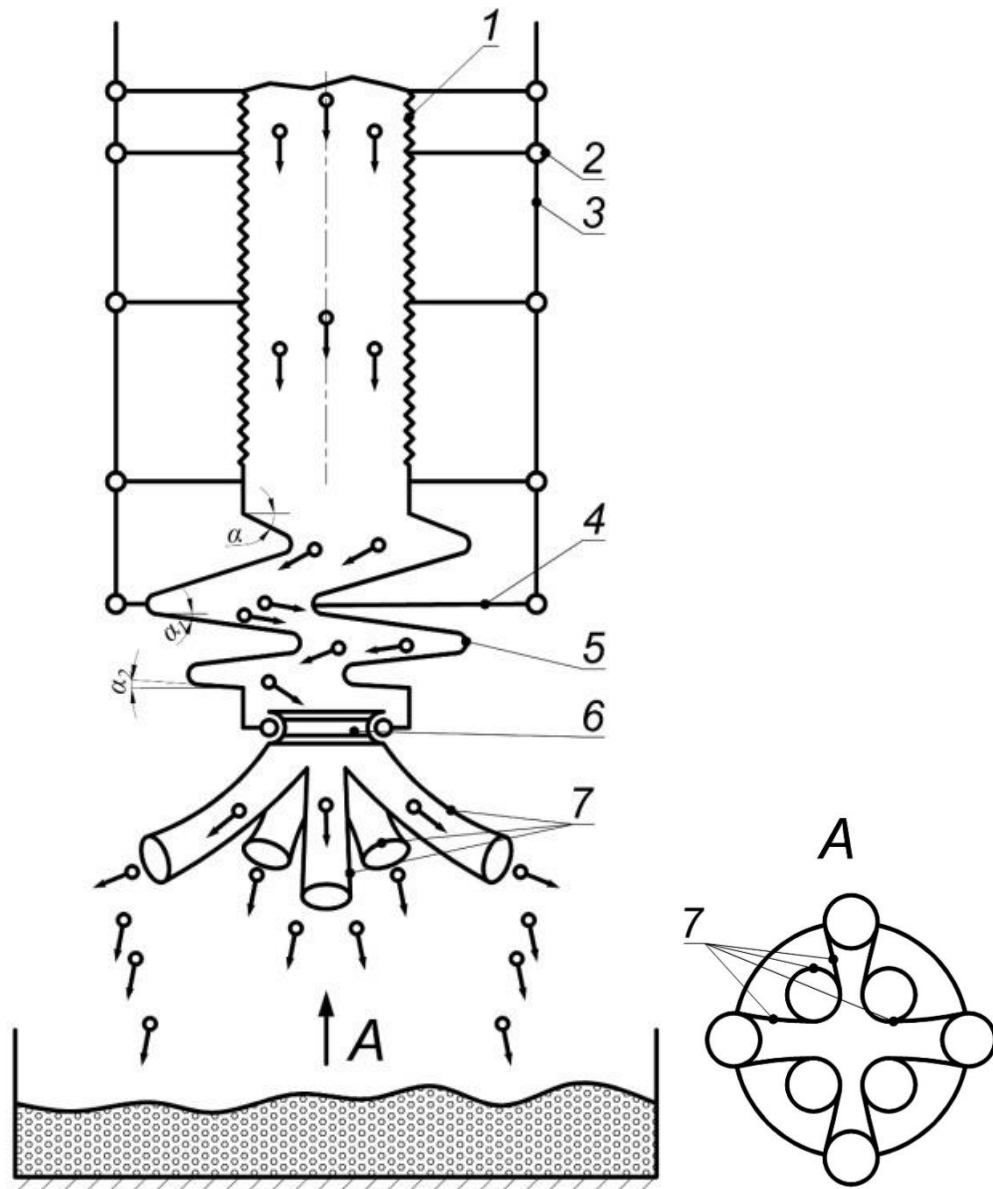
Thus, the use of overflow shelves and a truncated conical distributor reduces the kinetic energy of grain motion, minimizes deformation and damage, and ensures uniform filling over the entire area, reducing segregation of the grain heap. The use of simple geometric elements simplifies manufacturing and installation.

Figure 2.25 shows a device for uniform loading of a silo with grain, in which the most intensive downward movement of grain occurs in a special head unit [71].

The device consists of a corrugated sleeve 1 with ring-shaped guides 2 and cables 3; a drive mechanism (not shown) for raising and lowering the sleeve; flexible links 4; and a segmented screw channel 5. The inclination angles of the generating helix of each segment of the channel 5 decrease with distance from the sleeve outlet cross-section: $\alpha > \alpha_1 > \alpha_2$. The angles α , α_1 , and α_2 exceed the external friction angle of grain. A head 6 with tube outlets 7 of different lengths and directions is fixed at the lower part of the channel 5.

The device operates as follows. For loading an empty silo, the sleeve 1 is extended together with the screw channel 5 and head 6. Grain is fed to the upper part and flows downward under gravity. Upon reaching the screw channel 5, the grain velocity continuously changes in magnitude and direction. In the screw channel, the grain decelerates due to changes in the velocity vector and the reduced inclination angles of the channel segments. From the screw channel 5, grain enters the head 6 and is distributed among the tube outlets 7. Since the tube outlets have different lengths, grain is discharged from the head 6 uniformly and falls evenly over the entire heap surface in

the silo. This significantly reduces segregation, decreases grain damage, and reduces packing density.



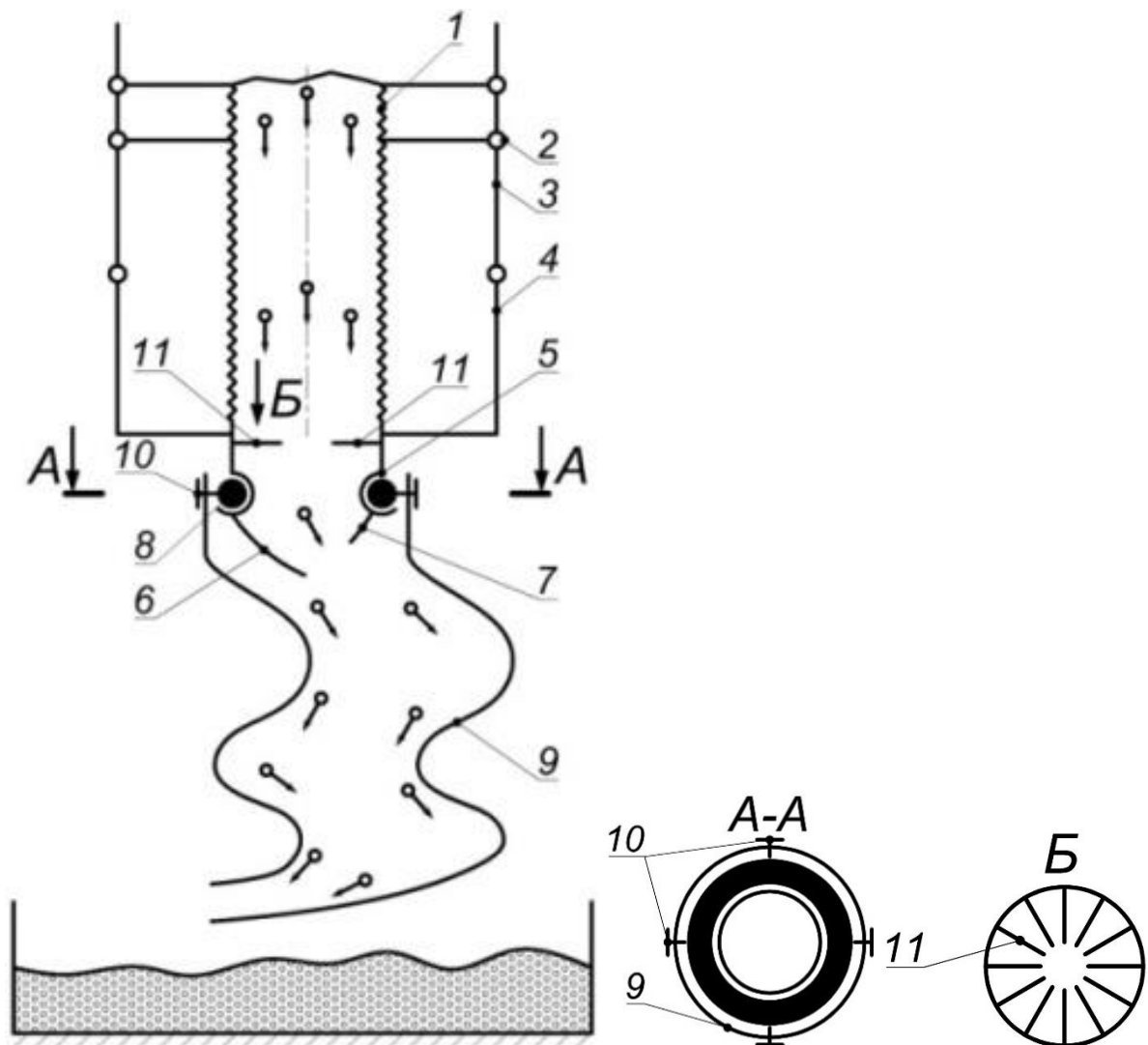
1 – corrugated sleeve; 2 – guide rings; 3 – cable; 4 – fasteners; 5 – screw channel; 6 – cylindrical head; 7 – tube outlets

Figure 2.25 – Device for uniform loading of a silo with grain

Thus, the screw channel and the head with tube outlets provide uniform filling over the entire silo area, reducing segregation and lowering pressure on the silo walls and bottom, while also simplifying manufacturing and installation due to simple geometric elements.

For uniform and damage-free delivery of grain into a container (Fig. 2.26), a screw-type loading device is proposed [72].

The screw-type loading device consists of a corrugated sleeve 1 with ring-shaped guides 2 and cables 3; a drive mechanism (not shown) for raising and lowering; flexible links 4; hemispherical links 5 in the lower part; guide plate 6 and protective plate 7; a cylindrical ring 8 inside the links 5; and a screw channel 9 attached to the ring 8 by screws 10. In the upper part of the hemispherical links, radially directed elastic rods 11 are uniformly fixed around the entire inner diameter, perpendicular to the longitudinal axis of sleeve 1.



1 – corrugated sleeve; 2 – guide rings; 3 – cable; 4 – cable fixing devices; 5 – hinge;
6, 7 – guide plates; 8 – screw channel; 10 – screws; 11 – elastic rods

Figure 2.26 – Screw-type loading device

The device operates as follows. For loading an empty silo, the sleeve 1 is extended together with the screw channel 9 down to the silo bottom. Grain is fed to the upper part

and flows downward under gravity. Upon reaching the elastic rods 11, the grain is slightly slowed as it enters the screw channel 9. The guide plate 6 and protective plate 7 concentrate the grain flow into the screw channel 9. Inside the screw channel, the grain velocity continuously changes in magnitude and direction. The helical motion generates a centrifugal force that rotates the screw channel 9 around its vertical axis. Due to changes in the velocity vector and the screw pitch, the grain decelerates and the impact force on the silo base is reduced. Rotation of the screw channel 9 promotes more uniform heap formation and reduces segregation.

Thus, the use of a screw channel with a decreasing pitch and elastic rods reduces the kinetic energy of grain, minimizes deformation and damage, and ensures uniform filling, thereby reducing segregation. Simple geometric elements also simplify the design.

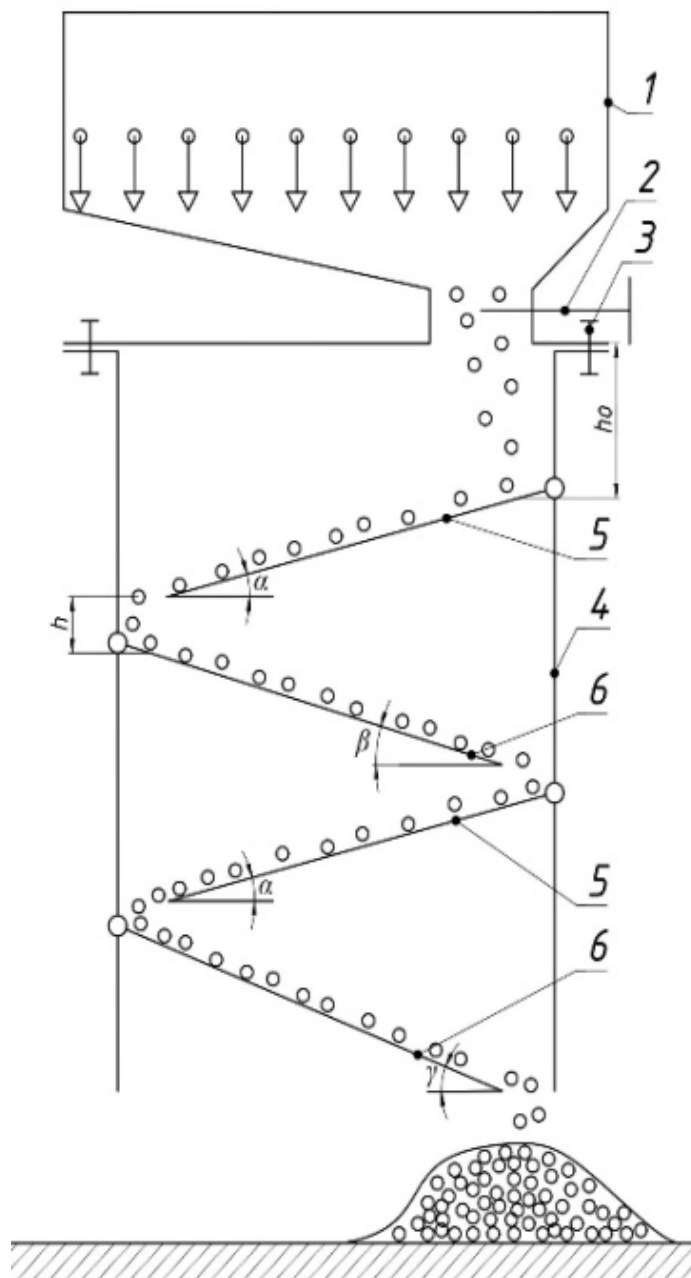
To load grain into silos using a braking effect, a gravity–cascade loading unit is proposed [73] (Fig. 2.27).

The main elements of the gravity–cascade loading unit are a loading hopper 1 and a parallelepiped-shaped metal housing 4, connected by bolted joints 3. A slide gate 2 is used to regulate the grain flow leaving the hopper and entering the housing. Inside the housing 4, an alternating cascade of acceleration shelves 5 and braking shelves 6 is arranged along its full height. The group of acceleration shelves 5 is placed on one side of the housing 4, while the braking shelves 6 are placed on the opposite side. The upper edge of the first acceleration shelf 5 is located directly beneath the gate 2 at a distance h_0 . Each acceleration shelf 5 has the same inclination angle α to the horizon and is positioned above a braking shelf 6. The distance between the lower edge of each shelf and the upper edge of the next lower shelf is a constant fixed distance h . The braking shelves 6 are set at different inclination angles: the first at angle β and the second at angle γ . The angles β and γ are smaller than the common angle α of the acceleration shelves 5.

The unit operates as follows. Grain flows from hopper 1 through the slide gate 2, which regulates flow intensity, and enters the housing 4. The first interaction occurs at the upper edge of the first acceleration shelf 5 located at a fixed distance h beneath the gate.

Under gravity, grain slides along the acceleration shelf 5 at angle α and gradually accelerates. Reaching its edge, the grain falls onto a braking shelf 6 located a distance h below. The braking shelves have gentler angles (β and γ), creating greater frictional resistance, which decelerates the flow and prevents accumulation.

The process then repeats: after braking, the grain falls onto the next acceleration shelf 5 and accelerates again, but on the next braking shelf 6 its velocity is reduced to a level close to the initial value. Due to this alternation of acceleration (5) and braking (6) sections, smooth and safe movement of grain inside the housing 4 and its soft discharge without impact loads and without the risk of arching are ensured.



1 – hopper; 2 – slide gate; 3 – bolts; 4 – rectangular metal housing; 5 – acceleration

Figure 2.27 – Gravity–cascade loading unit

Among the described methods, the cascade method of loading silos with grain is the most effective. It should be used for loading tall silo structures. However, grain flow along a rough surface is characterized by considerable spatial non-uniformity. Such non-uniformity results in the highest concentration of the solid phase and an increased content of large and dense kernels in the central part of the grain layer. At the same time, at the peripheral parts of the flow, which have increased intergranular space, a higher concentration of light particles is observed.

The analysis of loading devices indicates that:

- gravity loading devices are the most widespread because they are simple to manufacture and do not require a drive; however, their effectiveness is achieved in medium-size containers (cylinder height not exceeding 5 m);
- driven loading devices are more suitable for containers with cross-section diameters exceeding 3 m and with a depth limited to 3 m;
- for loading tall cylindrical bins (container height more than 15 m), corrugated sleeves with cascade-descent attachments at their lower part should be used.

CHAPTER 3. MATHEMATICAL MODELING OF THE GRAIN LOADING PROCESS INTO A SILO

3.1 Features of the Operation of Silo Structures

It is known that the bulk storage method is widely used for storing large batches of grain. In this case, various types of storage facilities are employed, including silos, stationary and mobile bunkers, and containers. The use of bulk grain storage ensures stable operation of the entire technological complex, including elevator facilities. This method makes it possible to increase the level of mechanization and automation of the entire elevator production process. In addition, bulk storage using silos improves labor productivity, increases the utilization factor of elevator capacities, and minimizes the use of manual labor at all stages of silo operation. The bulk method of grain storage does not require packaging materials (such as bags, etc.), which reduces grain losses during storage.

Elevator facilities use silos of various designs and sizes. The height of silos may range from 20 to 60 m and depends on the bearing capacity of the stored grain or other bulk materials. Silo walls are typically made of corrugated galvanized steel, which increases structural strength while simultaneously reducing weight. Silos may be equipped with conical bottoms intended for temporary storage with gravity discharge of bulk material, or with flat concrete bottoms that ensure long-term and high-quality storage of grain. Mobile storage systems are also used.

Silos used at elevator facilities possess several advantages unique to this type of structure. These advantages can be grouped into five categories:

- the possibility of integration with various continuous and batch-processing technological equipment;
- the ability to store different grades of grain over a wide range of volumes while maintaining high preservation quality;
- the capability to regulate the throughput capacity of discharge openings;
- low energy consumption during loading, especially under gravity loading conditions;

- low operating costs.

It is known that during silo operation, negative phenomena associated with grain discharge from storage facilities may occur [74–76]. Under certain conditions caused by the combined influence of various factors, grain discharge may become unstable or even completely stop. Such phenomena may arise due to [77]:

- formation of static and dynamic arches above discharge openings;
- adhesion of grain material to the silo walls;
- compaction pressure during loading of tall storage facilities, causing a sudden increase in pressure in the lower part of the silo at the initial stage;
- incomplete utilization of the effective storage volume;
- deterioration of the initial quality of grain material due to segregation, caking, mechanical damage, lump formation, and other similar structural changes in the bulk material.

The occurrence of such undesirable phenomena leads to destabilization of the entire technological process of loading and unloading silos at elevator facilities. As a result, unloading time increases, which in turn causes longer idle periods for transport equipment (e.g., railway wagons). Restoring normal silo operation requires significant energy consumption and heavy manual labor, often resulting in violations of occupational safety regulations.

The operational stability of silos at modern elevator facilities [78] is influenced by a number of internal and external factors. Internal factors include the physicommechanical and biological properties of the stored material, while external factors comprise environmental conditions as well as structural and technological parameters of the silo and its auxiliary equipment.

The primary factor is the flowability of the grain material. Moisture content also has a significant impact on flowability, especially during discharge. When wheat moisture content exceeds 14.5%, surface moisture may appear, increasing the coefficients of friction and adhesion between grains. This reduces flowability and increases the angle of repose [79]. Wet grain (moisture content above 17%) exhibits the poorest flowability and may cause blockages in grain pipelines and bunkers [80].

Adhesion, cohesion, and autohesion also have a significant influence on silo operation stability. These phenomena arise from the interaction of grain material with silo surfaces and between individual kernels.

Adhesion refers to surface phenomena and characterizes the interaction between silo structural surfaces and individual grain kernels. The tendency of grain layers to adhere to walls (especially near discharge openings) is determined by adhesion forces; therefore, external воздействие (external action) is required to disrupt these bonds.

Cohesion characterizes the interaction between molecules of bulk material and, during long-term grain storage, leads to the formation of agglomerates (lumps), which in turn disrupts stable silo operation.

Autohesion most often manifests during the storage of mechanically damaged grain and is a primary cause of grain caking. This phenomenon may occur during gravity loading of silos and significantly impedes efficient grain discharge.

Compaction of the grain bulk has a substantial effect on the operation of silos of various designs. The degree of compaction depends on the loading method, storage duration and conditions, as well as the physicomachanical and biological properties of the material. As compaction increases, internal friction and initial shear resistance also increase. An increase in initial shear resistance leads to the formation of stable arches above discharge openings, hindering free material flow.

Grain loading into silos directly affects all the processes described above. When grain falls from a considerable height, it forms the highest packing density in the lower part of the silo. The packing density decreases as the silo fills. Impact and static loads affect grain compaction differently.

During silo loading, segregation occurs, i.e., separation of grain material by particle size distribution. Segregation typically arises during gravity loading. Two characteristic zones of segregation can be identified:

- the free-fall zone, defined by the distance between the loading opening and the surface of the bulk material;
- the bulk formation zone.

In the free-fall zone, the bulk material separates into fractions. The degree of segregation depends on the falling height and the physicommechanical properties of the grain. Fractional segregation significantly affects the discharge process.

In the bulk formation zone, segregation occurs due to the intensive rolling of heavier kernels toward the silo walls. To prevent grain segregation, uniform distribution of the material over the entire perimeter of the storage facility must be ensured.

3.2 Operation Process of the Transport System for Grain Loading into Silos at Elevators

A clear representation of the operation process of the transport system for loading grain into silos at an elevator can be presented in the form of a parametric model. Such a model makes it possible to identify all influential factors at each stage of grain transportation to silo storage facilities and to trace the role and position of the technological process under study.

The elevator transport system is located in the working tower, the above-silo galleries, and within the silo structure itself. In the working tower, the grain material is lifted upward by a bucket elevator, where it is processed and then delivered by horizontal conveyors located in the above-silo galleries to the loading device installed inside the silo. Let us consider the operation of such a technological system.

The process of loading silos with grain consists of three consecutive stages:

- at the first stage, the grain material is lifted to a certain height;
- at the second stage, the grain material is conveyed by horizontal scraper conveyors to the silo loading inlet;
- at the third stage, the silo is filled using a device that reduces the velocity of grain movement.

A parametric model provides a clear representation of the operation of such a transport system. It allows all factors influencing the technological process of silo loading to be comprehensively analyzed.

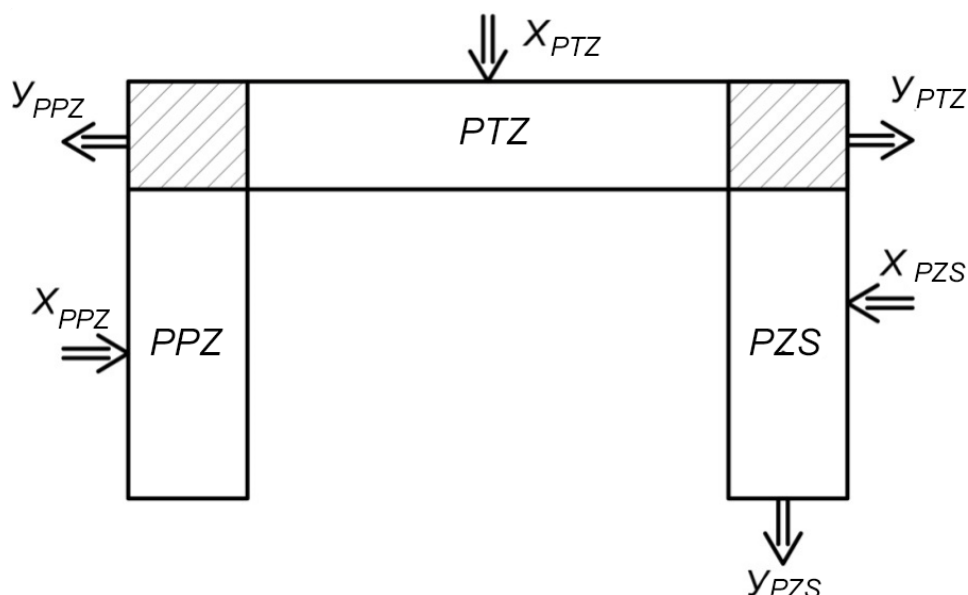


Figure 3.1 – Parametric model of the operation of the transport system for grain loading into silos

Let us denote the three interrelated transportation processes as follows: lifting the grain material to the required height (PPZ); transportation of the grain material by horizontal conveyors in the above-silo galleries (PTZ); loading the silos with grain using special braking devices (PZS). At each stage, the transportation process is influenced by both external and internal factors. External factors include geometric and kinematic parameters of conveyors, parameters of loading and transfer devices, physicochemical properties of the grain material, and the effects of previous stages of the technological process. The influence of factors at each stage is represented in the form of functions [81], whose arguments are the corresponding factors characterizing grain injury, damage, or complete destruction of kernels.

Figure 3.1 presents a parametric model of the operation of the transport-loading system of the elevator. The diagram shows the input parameter vectors: $\bar{X}_{\Pi\Pi3}; \bar{X}_{\Pi T3}; \bar{X}_{\Pi3C}$; де $\bar{X}_{\Pi\Pi3}$ - describes the conditions of grain lifting by the bucket elevator (geometric parameters of buckets, bucket spacing on the belt, belt speed, physicochemical and biochemical properties of the grain material); $\bar{X}_{\Pi T3}$; describes the process of horizontal transportation of the grain material in the above-silo galleries to the silo loading inlet (geometry of the galleries and scraper conveyors, physicochemical and biochemical properties of the grain material); $\bar{X}_{\Pi3C}$

characterizes the movement of the grain material inside the silo (parameters of the gentle loading device and properties of the grain material).

The degree of grain damage at each identified stage is evaluated by the functions $\bar{Y}_{\Pi\Pi3}$; $\bar{Y}_{\Pi T3}$; $\bar{Y}_{\Pi3C}$; де $\bar{Y}_{\Pi\Pi3}$, where $\bar{Y}_{\Pi\Pi3}$ expresses the influence of the bucket elevator on grain damage; $\bar{Y}_{\Pi T3}$ reflects the influence of the working elements of above-silo conveyors on grain damage; $\bar{Y}_{\Pi3C}$ describes the final stage of loading silos with grain.

The following factors affect grain injury, damage, or complete destruction during transportation and loading into silos:

- geometric parameters of transport and loading devices;
- kinematic parameters of bucket elevators and scraper conveyors;
- physicommechanical properties of the grain material.

In experimental studies, these parameters can be used both to compare different transport-loading methods and devices and to analyze a specific device individually. The factors affecting grain integrity during operation of the bucket elevator include:

- x_{1z} – geometric parameters of the bucket;
- x_{2z} – geometric parameters of the upper head of the bucket elevator;
- x_{3z} – spacing between buckets on the belt;
- x_{4z} – bucket speed;
- x_{5z} – reverse spillage of kernels;
- x_{6z} – type of loading;
- x_{7z} – physicommechanical properties of grain;
- x_{8z} – compression and pinching of kernels.

Grain damage in bucket elevators occurs due to the impulse resulting from the difference in the direction vectors of the kinetic energy of the grain and the buckets during collision. During elevator operation, impact effects on the grain are observed: sliding impact of buckets on the upper grain layers in the lower head, impact during bucket filling, collision with simultaneous sliding in the upper head, and “reverse spillage” of grain into the return branch. Figure 3.2 presents a diagram of the influence of kinematic and geometric parameters of bucket elevators on kernel damage.

Changes in structural parameters x_{1z} , x_{2z} , x_{3z} lead to changes in the kinematic parameter x_{4z} and to a reduction in parameters x_{5z} and x_{8z} . Modification of design

parameters alters the operating mode of the elevator, reduces impact forces, and consequently decreases grain damage.

The factors listed above are combined, depending on their significance and the research methodology, into the functional X^{PPZ}.

The output parameters of the vertical lifting process by bucket elevators are evaluated using the following criteria:

y_{1z} – integrity or damage of grain kernels;

y_{2z} – energy consumption for lifting the grain material.

Parameter y_{1z} characterizes the integrity of grain kernels during discharge and depends on the design and kinematic parameters of the elevator as well as on the physicommechanical properties of the grain

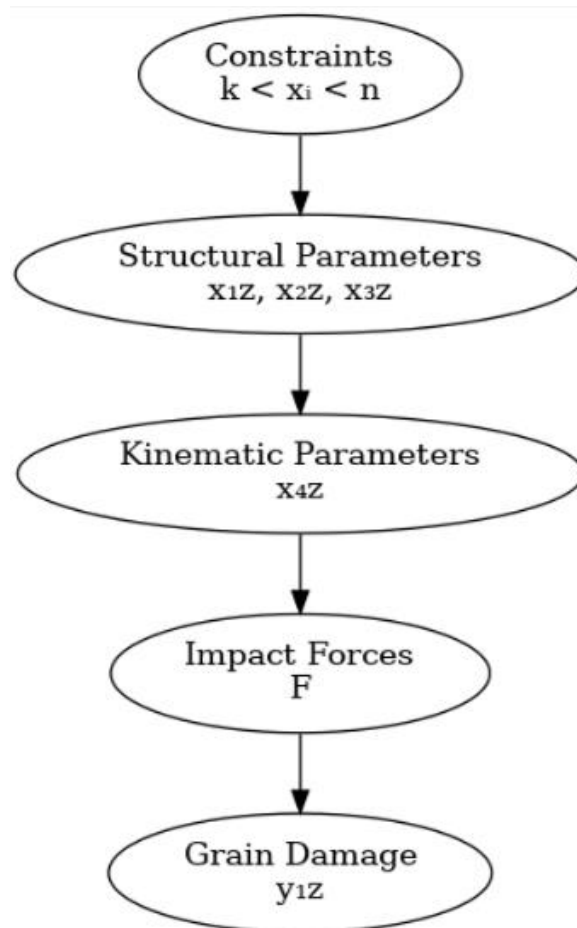


Figure 3.2 – Influence of kinematic and geometric parameters of bucket elevators on kernel damage

Transportation of the grain material to the silo inlet is performed by scraper conveyors. The following parameters affect the operation of scraper conveyors located in the above-silo galleries:

z_{1z} – direct contact of the traction element of the scraper conveyor with structural elements of the gallery;

z_{2z} – conveyor speed;

z_{3z} – scraper type;

z_{4z} – material of the scrapers;

z_{5z} – physico-mechanical properties of the grain.

Scraper conveyors are strategically important and, in terms of reliability and techno-technological characteristics, are among the most suitable for the elevator industry [82, 83]. Their main disadvantage is grain damage, which increases the broken grain coefficient.

The output parameters of horizontal transportation to the silo loading inlet are evaluated by:

y_{3z} – integrity or damage of grain kernels;

y_{3z} – energy consumption for transporting grain to the silo inlet.

Speed regimes significantly affect product quality. Grain kernels in the conveyor casing are subjected to impact loads caused by cyclic impulses from the traction element with scrapers.

The technological process of loading silos with grain is characterized by the following parameters:

ϑ_{1z} – presence or absence of a loading device;

ϑ_{2z} – presence or absence of a drive;

ϑ_{3z} – complexity or simplicity of device manufacture;

ϑ_{4z} – versatility of the device.

These factors form the functional $\bar{X}_{\Pi 3C}$. The output parameters of the silo filling process using loading devices are the object of this study. The main criteria are:

y_{4z} – dynamic effect of the grain material on the lower layers of the bulk;

y_{5z} – degree of grain damage;

y_{6z} – degree of grain segregation.

Thus, silo operation can be represented as:

$$\bar{X}_{PPZ} = \bar{X}_{PPZ}(\vartheta_{13}, \dots, \vartheta_{n3}), \quad (3.1)$$

$$\bar{Y}_{PPZ} = \bar{Y}_{PPZ}(y_{43}, \dots, y_{n3}). \quad (3.2)$$

Factor y_{4z} affects storage duration and discharge stability, while factors y_{5z} and y_{6z} affect the quality of the final product.

The stages of operation of the elevator transport system are shown in Figure 3.1 as three interconnected functional blocks. Let us introduce the following notation.

Let $(x_{1z}, \dots, x_{nz})$ be parameters affecting the grain lifting process by bucket elevators. Let S^n denote the space of these parameters, $x_i \in S^n$.

Let $f(x_{1z}, \dots, x_{nz})$ be a vector function describing the lifting process:

$$f(x_{13}, \dots, x_{n3}) = (y_{i3}, \dots, y_{k3}); \quad (3.3)$$

where

$$y_{i3} = y_{i3}(x_{13}, \dots, x_{k3}), i = 1 \dots k. \quad (3.4)$$

The output parameters y_{1z}, y_{2z} form the set $y_i \in S^k$. Hence,

$$S^n \xrightarrow{f_1} S^k. \quad (3.5)$$

After lifting, parameters $(y_{1z}, \dots, y_{kz})$ influence the horizontal transportation process and become internal parameters, while external parameters $(z_{1z}, \dots, z_{mz})$ are added. Let $z_i \in S^m$. Thus, the process is influenced by parameters from $S^k \times S^m$.

The transportation function is:

$$f(x_{13}, \dots, x_{n3}, z_{13}, \dots, z_{m3}) = (h_1, \dots, h_{l3}), \quad (3.6)$$

$$p_i = p_i(y_{i3}, \dots, y_{k3}, z_{13}, \dots, z_{m3}), h_i \in S^l \quad (3.7)$$

Thus,

$$S^k \times S^m \xrightarrow{f_2} S^l \quad (3.8)$$

Loading silos with grain is a crucial stage affecting the entire technological process and final product quality.

Let $(\vartheta_{1z}, \dots, \vartheta_{rz})$ be parameters influencing the loading process, $(\vartheta_{1z}, \dots, \vartheta_{rz}) \in S^h$. Parameters $(h_1, \dots, h_{l3}) \in S^l$ also affect loading.

The loading function is:

$$g((h_1, \dots, h_{l3}, \vartheta_{1z}, \dots, \vartheta_{rz})) = Y, \quad (3.9)$$

where Y is the output parameter evaluating grain damage during loading.

Thus,

$$S^l \times S^h \xrightarrow{f_3} S, \quad (3.10)$$

where S is a one-dimensional space.

By combining equations (3.5), (3.8), and (3.10) into a sequential chain, we obtain a mathematical model describing the operation of the transport system for loading silos at modern elevator enterprises.

$$S^n \xrightarrow{f_1} S^k.$$

$$S^k \times S^m \xrightarrow{f_2} S^l. \quad (3.11)$$

$$S^l \times S^h \xrightarrow{f_3} S$$

If all external parameters influencing grain damage are shifted to the beginning of the process, the model becomes:

$$S^N \xrightarrow{f_1} S^K \xrightarrow{f_2} S^L \xrightarrow{f_3} S, \quad (3.12)$$

where $N \neq n, K \neq k, L \neq l$.

In practice, studies of silo loading used input parameters of the loading device and physicommechanical properties of the grain material.

The selection of transformations f_1, f_2, f_3 for evaluating transport system efficiency can be performed using classical qualimetry methods [84]. For elevator transport systems, all transformations are linear. Therefore, the problem of studying grain damage during silo loading reduces to a classical linear algebra problem.

Thus, regardless of the form of functions f_1, f_2, f_3 their numerical representation is always possible. The main task is the correct selection of silo loading system parameters that affect the entire loading process and make it possible to reduce grain damage.

3.3. Mathematical Modeling of the Impact Interaction of Grain with the Concrete Bottom of a Silo

3.3.1 Determination of the Force Characteristics of Grain during Impact with a Rigid Obstacle

The impact interaction of grain with other solid bodies during its loading into silos leads to the occurrence of local contact deformations and maximum pressure at the contact point between the grain kernel and the concrete bottom of the silo. During impact, microcracks, fractures, dents, and other types of damage may appear in the kernels [85]. In order to reduce or completely eliminate such damage, special devices should be installed inside silos to reduce the falling height and the velocity of grain kernels.

The concrete bottom of a silo is a flat, absolutely rigid surface, which is assumed to be an elastic half-space formed by a horizontal plane with its own Young's modulus and Poisson's ratio. To model the impact interaction of grain, the classical Hertz contact theory was applied, which makes it possible to determine local deformations and contact stresses arising in individual grain kernels [86–88]. The choice of this theory is justified by the small deformations of grain during impact with concrete, which exhibit viscoelastic behavior.

Assuming that the gravitational force acting on a grain kernel during impact is negligible due to its small mass and short interaction time, the contact approach of the bodies after collision $x=x(t)$, according to Hertz theory, is described by the differential equation:

$$mx'' = -cx^{\frac{3}{2}}, \quad (3.13)$$

where c is a constant determined in this case by the radii of curvature of the spherical grain surface and the flat concrete surface, as well as by the corresponding elastic properties of the materials.

According to Hertz theory and [86, 87, 89], the following expressions apply:

$$c = \frac{4\sqrt{R_1}}{3Q} \cdot \frac{\left(1 + \frac{3}{8}\varepsilon^2 + \frac{15}{64}\varepsilon^4\right)^{\frac{1}{2}}}{\left(1 + \frac{\varepsilon^2}{4} + \frac{9\varepsilon^4}{64} + \frac{25\varepsilon^6}{256}\right)^{\frac{3}{2}}};$$

$$Q = \frac{1-\mu^2}{E} + \frac{1-\mu_n^2}{E_n}; \quad (3.14)$$

$$\varepsilon^2 = \sqrt{\frac{16\left(5+\frac{R_2}{R_1}\right)^2}{9\left(3+\frac{R_2}{R_1}\right)^2} + \frac{64\left(1-\frac{R_2}{R_1}\right)}{3\left(3+\frac{R_2}{R_1}\right)} - \frac{4\left(5+\frac{R_2}{R_1}\right)}{3\left(3+\frac{R_2}{R_1}\right)}};$$

Where m is the mass of a grain kernel; E, μ are the Young's modulus and Poisson's ratio of the grain; $R_1 \geq R_2$ are the radii of curvature of the grain; E_n, μ_n are the Young's modulus and Poisson's ratio of the horizontal contact surface.

From differential equation (3.13), the grain velocity equation is obtained:

$$x'' = \frac{dv}{dt} = \frac{dv}{dx} \cdot \frac{dx}{dt} = v \frac{dv}{dx};$$

$$v \frac{dv}{dx} = \frac{-c}{m} x^{\frac{3}{2}};$$

$$v dv = \left(\frac{-c}{m} x^{\frac{3}{2}} \right) dx. \quad (3.15)$$

Integrating both sides of equation (3.15) yields:

$$\frac{v^2}{2} + c_1 = c_2 - \frac{2c}{5m} x^{\frac{5}{2}};$$

$$\frac{dx}{dt} = \sqrt{2c_2 - c_1 - \frac{4c}{5m} x^{\frac{5}{2}}}. \quad (3.16)$$

Introducing the initial conditions into (3.16):

$$\begin{cases} x(0) = 0 \\ x'(0) = v' \end{cases},$$

where v – is the impact velocity of the bodies, taking into account the initial grain velocity V_0 .

Considering the initial conditions, the following expression is obtained:

$$\frac{dx}{dt} = \sqrt{v^2 - \frac{4c}{5m} x^{\frac{5}{2}}};$$

$$\frac{dx}{dt} = v \sqrt{1 - \frac{4c}{5mv^2} x^{\frac{5}{2}}} \quad (3.17)$$

Using equation (3.17), the maximum approach of the bodies during impact is determined:

$$1 - \frac{4c}{5mv^2} \gamma^{\frac{5}{2}}$$

hence

$$\gamma = \sqrt[5]{\left(\frac{5mv^2}{4c}\right)^2} = \left(\frac{5mv^2}{4c}\right)^{\frac{2}{5}}. \quad (3.18)$$

By integrating equation (3.17) over the interval $[0; \gamma]$ and taking into account (3.18), the duration of the impact interaction t of grain kernels is determined:

$$dt = \frac{2dx}{v\sqrt{1-\frac{4c}{5mv^2}x^{\frac{5}{2}}}};$$

$$t = \frac{2}{v} \int_0^\gamma \frac{dx}{\sqrt{1-\frac{4c}{5mv^2}x^{\frac{5}{2}}}}. \quad (3.19)$$

Substituting (3.18) into (3.19), the impact duration is obtained as:

$$t = \frac{2}{v} \int_0^\gamma \frac{dx}{\sqrt{1-\left(\frac{x}{\gamma}\right)^{\frac{5}{2}}}}. \quad (3.20)$$

Introducing the substitution $y=x/\gamma$, the final expression for the impact time becomes:

$$t = \frac{2\gamma}{v} \int_0^1 \frac{dx}{\sqrt{1-y^{\frac{5}{2}}}} = \frac{2\gamma}{v} \int_0^1 \left(1 - y^{\frac{5}{2}}\right)^{-\frac{1}{2}} dy = \frac{2\gamma}{v} I. \quad (3.21)$$

$$\text{where } I = \int_0^1 \frac{dy}{\sqrt{1-y^{\frac{5}{2}}}}.$$

For further solution, the integrand in equation (3.21) is expanded using the Maclaurin series:

$$I = \int_0^1 \left(\frac{1 + \frac{1}{2 \cdot 1!} y^{\frac{5}{2}} + \frac{3}{4 \cdot 1!} \left(y^{\frac{5}{2}}\right)^2 + \frac{15}{8 \cdot 3!} \left(y^{\frac{5}{2}}\right)^3 + \frac{105}{16 \cdot 4!} \left(y^{\frac{5}{2}}\right)^4 + \dots + 0,5 \cdot (0,5+1) \dots (0,5+(n-1))}{n!} \times \right. \\ \left. \left(y^{\frac{5}{2}}\right)^n \right) dy \quad (3.22)$$

After integration, the value of the integral is obtained:

$$I = \left(y + \frac{y^{\frac{7}{2}}}{7 \cdot 1!} + \frac{3y^{\frac{29}{4}}}{29 \cdot 2!} + \frac{15y^{\frac{133}{8}}}{133 \cdot 3!} + \frac{105y^{\frac{641}{16}}}{641 \cdot 4!} + \frac{945y^{\frac{3157}{32}}}{3157 \cdot 5!} + \frac{10395y^{\frac{15689}{64}}}{15689 \cdot 6!} + \frac{135135y^{\frac{78253}{128}}}{78253 \cdot 7!} + \dots \right) \bigg|_0^1 \approx 1,224.$$

Substituting $I=1.224$ into equation (3.21), the impact interaction time of a grain kernel with the silo bottom is obtained with an accuracy of 0.0001:

$$t = 2,448 \frac{\gamma}{v}, \quad (3.23)$$

Knowing γ and considering equation (3.18), the maximum contact force of interaction between a grain kernel and the concrete silo bottom is determined by:

$$F_{max} = c\gamma^{\frac{3}{2}}. \quad (3.24)$$

The maximum pressure is determined as:

$$P_{max} = \frac{3F_{max}}{2\pi\sigma_{max}b_{max}}, \quad (3.25)$$

Where

$$\sigma_{max} = \left(\frac{3}{4} Q F_{max} R_1 \left(1 + \frac{3}{8} \varepsilon^2 + \frac{15}{64} \varepsilon^4 \right) \right)^{\frac{1}{3}};$$

$$b_{max} = \sigma_{max} \sqrt{1 - \varepsilon^2}. \quad (3.26)$$

The maximum pressure arising during the contact interaction of grain with an absolutely rigid flat body corresponds to the internal stresses occurring within the grain kernel at the contact point. By calculating the maximum contact pressure and comparing

it with the average statistical strength limit $\sigma_{\max}$, the degree of grain damage can be assessed.

Obviously, when $P_{\max} > \sigma_{\max}$, grain deformation occurs and, consequently, grain damage. The type and degree of deformation of the grain mass depend on the extent to which $P_{\max} \gg \sigma_{\max}$.

3.3.2 Calculation of the main characteristics of the impact interaction of wheat when falling onto the concrete base of a silo

For the calculations, the following averaged data for winter wheat grain and the flat concrete surface of the silo were adopted [88]:

$$R_1=0.006 \text{ m}, R_2=1.5 \cdot 10^{-3} \text{ m}, m=4 \cdot 10^{-5} \text{ kg}, E=2,6 \cdot 10^6 \text{ Pa}, E_n=2 \cdot 10^{10} \text{ Pa}, \\ \mu=0.12, \mu_n=0.17, h=26 \text{ m}, V_0=0.65 \text{ m/s}, v = V_0 + \sqrt{2gh} \text{ m/s}.$$

According to the given initial data, using equation (3.14), the following parameters were determined:

$$\varepsilon^2=0.9384, Q=3,796 \cdot 10^{-8} \text{ Pa}, c=1.967 \cdot 10^6 \text{ m}^{1/2}/\text{Pa}.$$

Using equations (3.18) and (3.23–3.26), the main parameters of the interaction between a grain kernel and the concrete bottom of the silo were determined:

$$\gamma=7.158 \cdot 10^{-4} \text{ m}, t=7.545 \cdot 10^{-5} \text{ s}, F_{\max}=37.67 \text{ N}, a_{\max}=2.156 \cdot 10^{-3} \text{ m}, \\ b_{\max}=5.35 \cdot 10^{-4} \text{ m}, P_{\max}=15,598 \text{ MPa}.$$

At the same time, the average strength limit for winter wheat grain is $\sigma_{\max}=5 \text{ MPa}$. Comparing $\sigma_{\max}$ with the obtained results shows that the maximum contact pressure arising when winter wheat grain falls onto concrete significantly exceeds the maximum permissible value, i.e.,

$$P_{\max} \gg \sigma_{\max}.$$

According to the conducted study, during the loading of winter wheat into a silo, its lower layers are damaged as a result of elastic–plastic deformation of the kernels at their point contact with the concrete. This, in turn, may lead to deterioration of the lower layers of winter wheat during storage in the silo.

3.4. Mathematical Modeling of Impact Interaction between Individual Grain Kernels in a Grain Flow

The motion of grain material along a peripheral open helical channel (POHC), which is installed on the inner lateral surface of the silo (Fig. 2.19), occurs due to gravity and the mutual exchange of impact impulses between individual grain kernels within the grain flow. The flow regime of the bulk grain material is governed by the physical and mechanical properties of the grain being loaded into the silo. The surface of the grain may be smooth or glossy, rough, ribbed, uneven, or wrinkled [90]. These grain surface properties significantly affect the motion regime of the bulk grain material.

Let us consider the impact interaction of two grain kernels with mass m_{gm_gmg} located within an elementary volume of the grain flow and undergoing acceleration. The computational scheme of the elastic impact interaction between two wheat kernels is shown in Fig. 3.3.

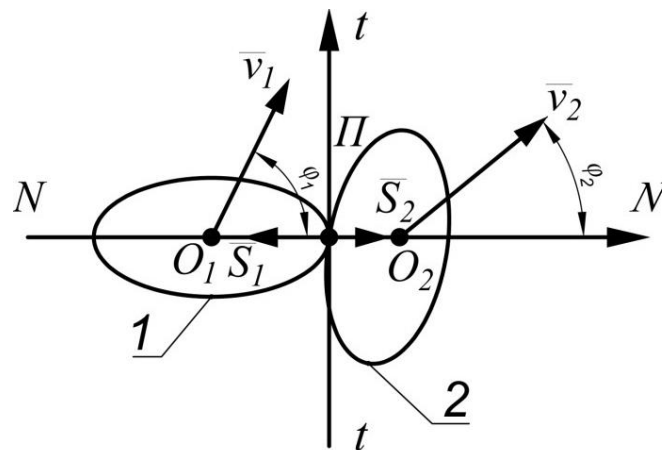


Figure 3.3 – Scheme of Impact Interaction Between Two Wheat Kernels

To simplify the description of the motion of individual wheat kernels along the working surface of the helical channel, the following assumptions were adopted: the line connecting the centers (O_1O_2) coincides with the line of action of the impulses (N–N); the velocities of the centers of mass of the kernels $\bar{v}_1$ i $\bar{v}_2$ do not lie along the line (O_1O_2) but are directed at certain angles φ_1 and φ_2 to it; moreover, during shear motion the kernels retain their mass and shape.

Through the contact point P of the two kernels, a common tangent t–t is drawn, which is perpendicular to the common normal N–N. These lines form a coordinate system with its origin at point P. To determine the impact impulses, unit vectors lying along the lines N–N and t–t are denoted by $\bar{i}$ and $\bar{j}$, respectively. Then the impact impulse acting on the first kernel is

$$S_1 = S \cdot \bar{i}_1, \text{ and } S_2 = S \cdot \bar{i}_2.$$

The velocity of the first kernel during its acceleration prior to impact with the second kernel is

$$\bar{v}_1 = v_{1x_1} \cdot \bar{i}_1 + v_{1y_1} \cdot \bar{j}_1, \quad (3.27)$$

$$\text{where } v_{1x_1} = -v_1 \cdot \cos \varphi_1; v_{1y_1} = v_1 \cdot \sin \varphi_1.$$

The velocity of the second kernel during its acceleration prior to impact with the first kernel is

$$\bar{v}_2 = v_{2x_2} \cdot \bar{i}_2 + v_{2y_2} \cdot \bar{j}_2, \quad (3.28)$$

$$\text{where } v_{2x_2} = +v_2 \cdot \cos \varphi_2; v_{2y_2} = v_2 \cdot \sin \varphi_2.$$

For the first kernel to strike the second one, the angle between the lines t–t and N–N must lie within the range from 0 to 90° [91, 92]. In the present case, this angle is equal to 90°.

In the further analysis of the impact interaction between two kernels, the following assumption is made: the colliding kernels have ideally smooth surfaces. As a result, after impact they do not rotate, i.e., the kernels undergo purely translational motion within the grain flow. In this case, according to Gauss's hypothesis [89,92], a relationship exists between the tangential and normal impulses, which is described by the expression

$$\Delta u = -u' \cdot f(1 + k), \quad (3.29)$$

where Δu is the change in relative tangential velocity; u' is the fluctuation (chaotic motion) velocity of the grain material within the selected elementary volume;

f is the coefficient of sliding friction between individual kernels during translational motion along the POHC; k is the coefficient of restitution.

The coefficient of restitution for an oblique impact between two individual kernels of mass m_g , according to [19], is characterized by the change in velocities before and after impact:

$$k = \frac{\vartheta'_{1x} - \vartheta'_{2x}}{\vartheta_1 \cdot \cos \varphi_1 - \vartheta_2 \cdot \cos \varphi_2}, \quad (3.30)$$

де ϑ_1, ϑ_2 – The coefficient of restitution for an oblique impact between two individual kernels of mass m_{gm_gm} , according to [19], is characterized by the change in velocities before and after impact; $\vartheta'_{1x}, \vartheta'_{2x}$ – are the velocities of the first and second kernels after impact, respectively.

A planar oblique central impact may occur when $\frac{\pi}{2} < \varphi_1 < \frac{3\pi}{2}$, $-\frac{\pi}{2} < \varphi_2 < \frac{\pi}{2}$ [92]. Based on these conditions and assuming that $m_{g1}=m_{g2}$, the relative tangential velocity of a kernel during its impact with another kernel is determined as

$$\Delta u = \vartheta_1 \cdot \sin \varphi_1 \pm \vartheta_2 \sin \varphi_2 \quad (3.31)$$

Substituting (3.30) and (3.31) into (3.29), the expression for determining the fluctuation velocity of kernels during their impact is obtained:

$$u' = -\frac{\Delta u}{f(1+k)} = -\frac{\vartheta_1 \cdot \sin \varphi_1 \pm \vartheta_2 \sin \varphi_2}{f(\frac{\vartheta_1 \cos \varphi_1 - \vartheta_2 \cos \varphi_2 + \vartheta'_{1x} - \vartheta'_{2x}}{\vartheta_1 \cos \varphi_1 - \vartheta_2 \cos \varphi_2})}. \quad (3.32)$$

It is known that the motion of individual kernels in the POHC flow has a rather complex functional character [92]. Therefore, the total kinetic energy of the mutual shear motion of two kernels with mass m_g can be represented as the sum of two components: translational and chaotic (fluctuational) motion energies of the grain in the peripheral open helical channel:

$$T_{sum.} = T_{cont.} + T_{var.}, \quad (3.33)$$

where T_{cont} is the kinetic energy of the translational motion of kernels along the helical channel, and T_{var} is the kinetic energy of the chaotic motion of kernels along the open helical channel. The components of the total kinetic energy are determined by the following expressions:

$$\begin{cases} T_{cont} = \frac{1}{2} m_3 (\Delta x)^2 \left(\frac{du}{dx} \right)^2 \\ T_{var} = \frac{1}{2} m_3 (u')^2 \end{cases}, \quad (3.34)$$

where $\Delta x = (b_1 - b_2)$ – is the difference between the coordinates of the centers of mass of the first and second kernels, $\left(\frac{du}{dx} \right)$ – is the velocity of bulk grain movement along the open helical channel.

Substituting (3.34) into (3.33) and taking into account that $m_g = V_g \rho_g$, we obtain:

$$T_{total} = 0,5 V_g \rho_g [(b_1 - b_2)^2 \left(\frac{du}{dx} \right)^2 + (u')^2], \quad (3.35)$$

where V_g is the volume of the i -th kernel and ρ_g is the bulk density of the grain.

During the shear motion of grain material along the acceleration section and especially during the transition from the acceleration section to the braking section, kernels continuously collide with each other. The average frequency of such impacts can be determined using the Ackermann–Schön formula [93]:

$$\gamma_3 = \frac{\tau \cdot du}{E_c n_3 dx}, \quad (3.36)$$

where n_g is the total number of kernels in the selected volume; τ – is the shear stress during gravitational shear of the grain material along the POHC; E_c – is the dissipation of kinetic energy during a single impact between two kernels.

The dissipation of kinetic energy is determined as [93]:

$$E_c = \frac{1}{2} m_3 c^2 \left(\frac{1-k^2}{4} + \frac{\mu(1+k)}{\pi} - \frac{\mu^2(1+k^2)}{4} \right) (u')^2 \quad (3.37)$$

The dissipation of kinetic energy is determined as [93]:

$$E_c = \frac{1}{2} m_3 c^2 e_3 (u')^2, \quad (3.38)$$

where e_g is the relative fraction of the kinetic energy of a single kernel dissipated during each collision with other kernels in the grain layer.

Substituting expressions (3.38) and (3.32) into (3.36), the formula for determining the average frequency of kernel impacts in a bulk grain medium during an oblique central impact in the acceleration section of a gravitational installation is obtained:

$$\gamma_3 = \frac{2\tau \left(\frac{\vartheta_1 \cos \alpha_1 - \vartheta_2 \cos \alpha_2 + \vartheta'_{1x} - \vartheta'_{2x}}{\vartheta_1 \cos \alpha_1 - \vartheta_2 \cos \alpha_2} \right)^2 du}{f^2 m_3 n_3 e_c (\vartheta_1 \sin \alpha_1 \pm \vartheta_2 \sin \alpha_2)^2 dx} \quad (3.39)$$

The obtained relationships for the fluctuation velocity of kernels during impact (3.32) and the average impact frequency (3.39) can be used for further analysis and substantiation of the parameters of the technological process of loading silos with grain using the POHC.

3.5 Impact interaction of a falling grain kernel with a stationary base

3.5.1 Mathematical modeling of the interaction process between a corn kernel and the concrete bottom of a silo

When silos are loaded with grain material, individual kernels of this material, upon reaching the bottom, attain their maximum linear velocity. It is determined by the formula $\vartheta_k = \sqrt{2gH}$, where H is the height from which the grain is dropped onto the silo bottom. After striking the concrete bottom, the kernels rebound to a certain height h . There may be several such rebounds, but the first one is the most important. This means that during the first fall from height H onto the concrete bottom of the silo, the kernel experiences the maximum impact, and it may be injured or completely destroyed.

Kernels damaged in this way accumulate in the lower part of the storage bin, which in turn leads to self-heating and the development of harmful microorganisms. This means that spoilage or complete loss of the grain stored in the silo is possible in the lower layers.

Let us consider possible variants of a corn kernel falling onto the bottom of a silo structure. Figure 3.4 shows four variants of collision of a corn kernel with the stationary base of the silo by its different parts. Thus, in Fig. 3.4a, during collision with the stationary base, the center of gravity of the kernel is displaced relative to the direction of the reaction force by a distance l . As a result, in our opinion, the kernel acquires not only a vertical velocity ϑ_v , but also an angular velocity ω . These velocities cause the kernel to rebound from the obstacle in different and unpredictable directions. In other types of collision (Fig. 3.4b, c, d), as a rule, the kernels rebound upward with a possible deviation from the vertical.

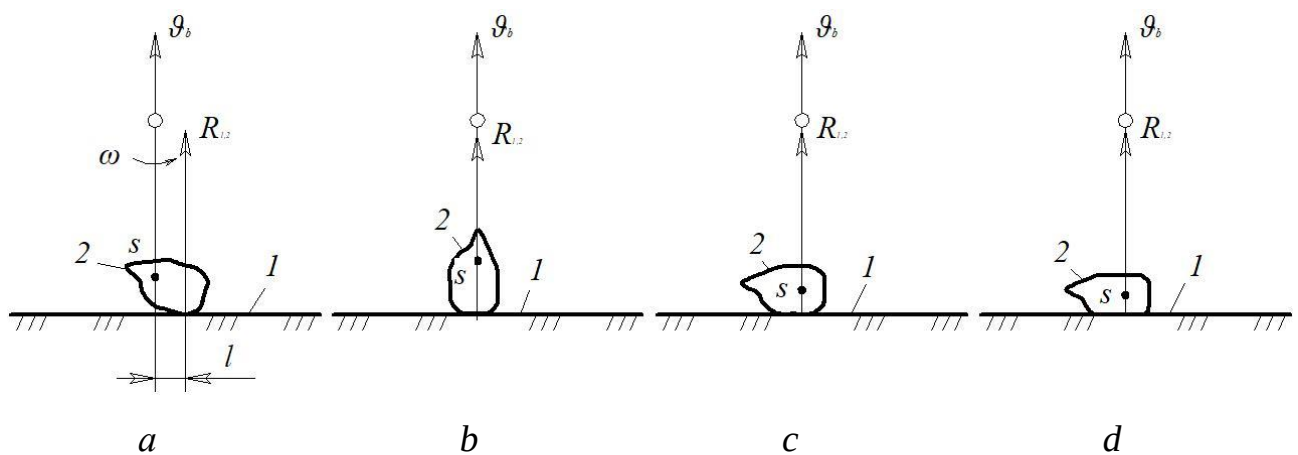


Figure 3.4 – Possible variants of collision of a corn kernel with the concrete bottom of a silo: 1 – massive silo bottom; 2 – corn kernel

Let us consider the case when a corn kernel rebounds vertically upward. Figure 3.5 shows the fall of a kernel onto the concrete bottom with velocity ϑ_k and its subsequent rebound upward with velocity ϑ_v . During such an impact, the kinetic energy of the kernel is completely converted into deformation energy. This deformation generates impact waves inside the kernel, which propagate intensively throughout its interior. The more intense the deformation waves, the lower the resistance of the kernels to damage.

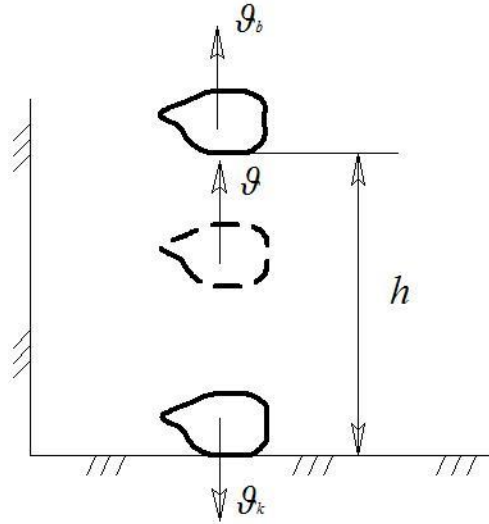


Figure 3.5 – Fall of a corn kernel onto the silo bottom followed by a vertical rebound to a height h

It is known that at the initial stage of filling silos with grain, the greatest grain damage occurs. The degree of kernel injury at this time directly depends on the velocity of kernel movement and the fall height [94].

The conditions under which destruction of kernels, for example corn kernels, does not occur during their impact interaction with a stationary obstacle are theoretically described using impact theory. In scientific literature, there are many definitions of mechanical impact. In the discipline of strength of materials, impact is defined as a process of short-term interaction of one body with another, in which the kinetic energy of these bodies is transformed into deformation energy [89, 94].

When a corn kernel falls onto the silo bottom, its kinetic energy is converted into the potential energy of the kernel itself. Then

$$T_p - T_k = U, \quad (3.40)$$

where T_p and T_k are, respectively, the kinetic energy of the corn kernel before impact and after impact against a stationary obstacle, J ; U is the potential deformation energy, J .

The kinetic energy of the kernel at the moment of impact with the obstacle is determined by the formula:

$$T_p = m_z g \cdot H, \quad (3.41)$$

where m_z is the mass of the corn kernel, kg; H is the height from which the kernel falls onto the concrete bottom of the silo, m.

After the collision of the kernel with the silo base, its velocity changes in magnitude and direction. The rebound velocity is related to the velocity with which the kernel falls onto the silo bottom by the following relationship:

$$\mathcal{G}_s = \mathcal{G}_k \cdot k_v, \quad (3.42)$$

where k_v is the coefficient of restitution.

Let us consider the kernel fall shown in Fig. 3.4a. The kinetic energy of the kernel after rebounding from a massive obstacle will be equal to:

$$T_k = \frac{m_z \cdot \mathcal{G}_s^2}{2} + \frac{I_s \cdot \omega^2}{2}, \quad (3.43)$$

where I_s is the moment of inertia of the kernel, $kg \cdot m^2$.

Substituting the obtained expressions into the energy balance equation (3.40), performing some transformations, and taking into account that $I_s = m_z l^2$, we obtain the equation for the potential energy accumulated by the corn kernel and the concrete bottom of the silo:

$$U = m_z [gH (1 - k_v^2) - 0,5 l^2 \omega^2]. \quad (3.44)$$

The obtained formula shows that the potential deformation energy of the kernel depends on the kernel mass and the falling velocity.

The potential deformation energy of a corn kernel is determined by the formula:

$$U_z = \frac{F_{imp} \cdot \Delta y}{2}, \quad (3.45)$$

where U_z is the potential deformation energy of the wheat kernel, J; F_{imp} is the maximum impact force of the kernel against a stationary base, N; Δy is the absolute deformation of the kernel, m.

It is known that the absolute deformation of a kernel is related to its dimensions and stiffness by the following expression:

$$\Delta y = \frac{F_{imp} \cdot a}{E_z \cdot S_z}, \quad (3.46)$$

where a is the thickness of the corn kernel at the point of impact ($a=2.5-3$); E_z is Young's modulus ($E_z=24.8-27.0$ MPa); S_z is the area of the deformed surface of the corn kernel ($S_z=0.000007-0.000008$ m²).

Substituting formula (3.46) into formula (3.45), we obtain:

$$U_z = \frac{F_{imp}^2 \cdot a}{2 \cdot E_z \cdot S_z}. \quad (3.47)$$

The obtained relationships make it possible to determine the accumulated potential energy and the factors influencing it. This provides an opportunity to understand and outline ways of reducing the impact interaction of kernels with a massive obstacle.

3.5.2 Experimental studies of corn kernel falling onto a concrete base

When corn grain falls onto the massive concrete bottom of a silo, an impact occurs, as a result of which deformation of the kernel arises at the point of impact. Its magnitude depends on the mass of the kernel and the velocity with which it strikes the silo base. The impact of the kernel against the obstacle causes impact waves to form inside the kernel. These waves propagate intensively throughout the entire volume of the kernel. The propagation velocity of impact waves, with some approximation, can be determined by the formula:

$$c = \sqrt{\frac{E_{grain}}{\rho}}, \quad (3.48)$$

where E_{grain} is the stress arising in the contact zone of the corn kernel with the concrete base of the silo, MPa; ρ is a complex parameter characterizing the state of the kernel during its deformation, MPa·s²·m⁻⁴.

The time of propagation of the impact wave throughout the entire kernel is determined by dividing the kernel length by the velocity c . Then, the total duration of the impact of the kernel against the obstacle will be:

$$\tau = \frac{2 \cdot b}{c}, \quad (3.49)$$

where b is the length of the kernel at the point of collision with the obstacle, m.

Example. Let us determine the impact characteristics of a falling kernel on the concrete bottom of a silo. For a corn kernel, let us assume that $E_z=26$ MPa, $b=0.009$ m, $\rho=0.00215$ MPa·s²·m⁻⁴.

Then, according to formula (3.48), the propagation velocity of the impact impulse in a corn kernel falling from a height $H=30$ m and having a mass $m_z=0.28$ g is $c=110$ m/s, which is approximately four times greater than ϑ_k . In this case, the total impact duration is $\tau=0.00016$ s.

Experimental studies of corn kernels falling onto a concrete base using photographic recording revealed the average rebound heights of kernels from the obstacle when dropped from different heights. Figure 3.6 shows the graph of the dependence of corn kernel rebound on the height from which it is dropped onto a stationary concrete base.

Based on the study results, restitution coefficients were determined for the selected heights from which the corn kernels were dropped. Thus, for $H=400$ mm, $k_v=0.525$, and for $H=1000$ mm, $k_v=0.435$. The average value of the restitution coefficient is $k_v=0.455$.

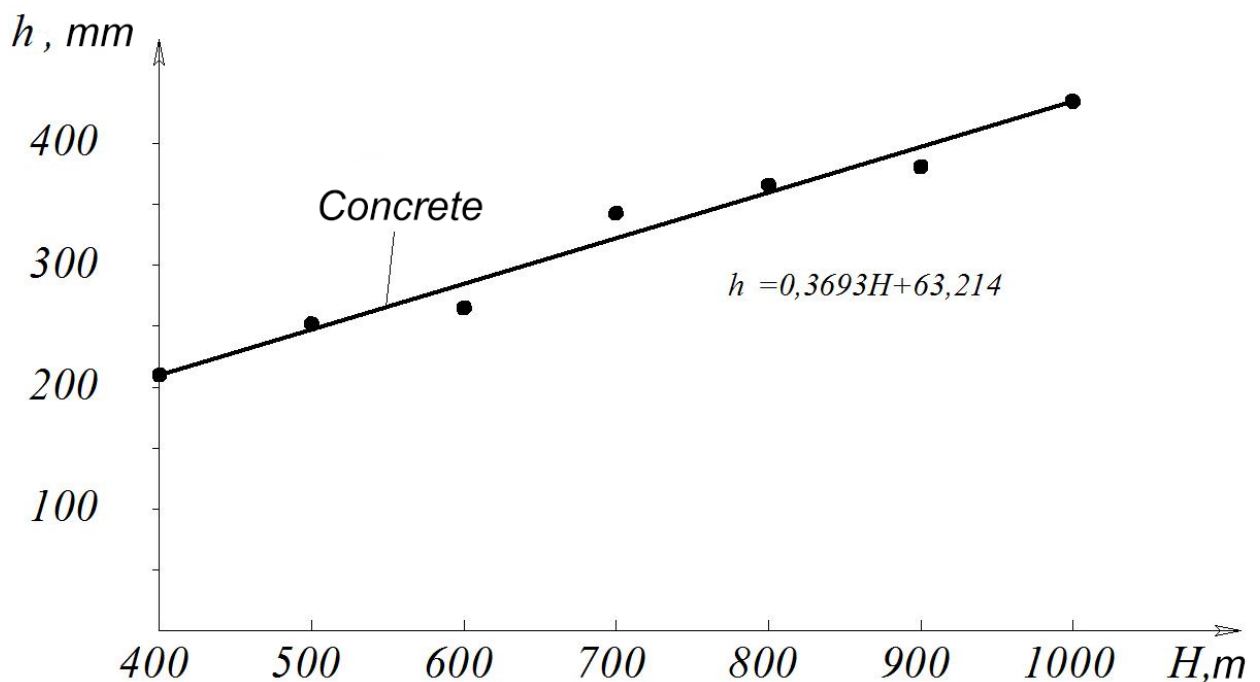


Figure 3.6 – Interaction of corn seeds when falling onto a concrete base

Further studies established that the potential energy of corn grain of the same variety and with identical physical and mechanical properties increases when the kernels are dropped from greater heights. Figure 3.7 shows the graph of changes in the potential energy of a corn kernel falling onto the concrete base of a silo.

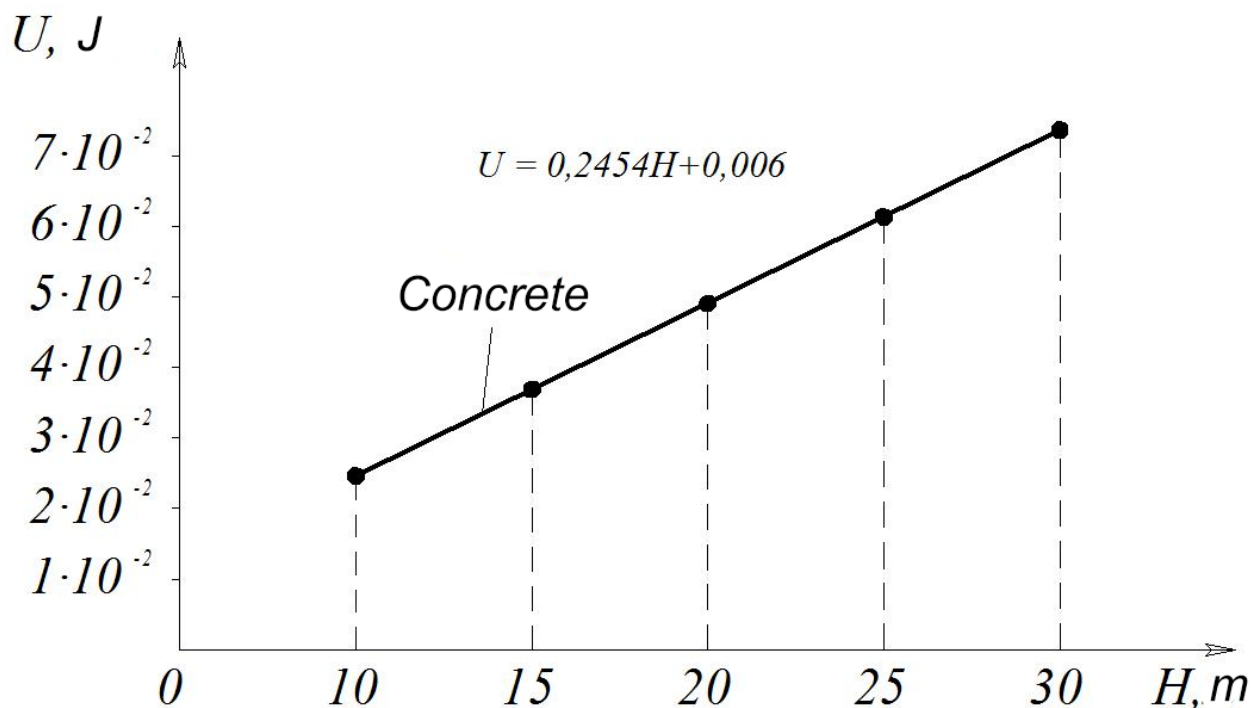


Figure 3.7 – Change in the potential energy of a corn kernel falling onto the concrete bottom of a silo from different heights

The graph shows that the potential energy of a corn kernel falling onto the concrete bottom of a silo increases with increasing fall height. To reduce the potential energy, braking devices should be installed at certain heights. With the help of these devices, it is possible to smoothly regulate the velocity of grain movement toward the silo bottom. Such measures should be implemented with minimal cost. Installed devices for reducing grain loading velocity lead to a reduction in kernel deformation and, consequently, to a decrease in kernel damage.

In order to reduce the degree of injury of kernels in the grain mass of corn at the initial stage of silo loading, it is necessary to create conditions under which part of the kinetic energy of kernel impact against the massive concrete bottom is converted into the potential energy of the working element of the braking device.

To reduce damage to kernels of bulk grain material inside the silo, it is necessary to install a corrugated sleeve with the possibility of lowering and raising it, and to fix a cone-type loading device at the lower part of this sleeve, the disks of which are covered with an elastic material (for example, rubber).

3.6 Mathematical Modeling of the Oblique Impact of a Falling Wheat Kernel on a Stationary Surface

3.6.1 Impact Interaction of Wheat Grain with the Concrete Bottom of a Silo

Reducing the impact interaction of grain with the working elements of machines and mechanisms is one of the indicators of the technical level of modern agricultural production. Therefore, many scientific publications have been devoted to the study of such impact interactions [85, 87, 95, 96, 97].

The issues of impact energy transfer, determination of force impulses, coefficients of restitution, and rebound during grain falling onto the concrete bottom of silos have not been sufficiently studied. This is due to the fact that grain material is delivered by overhead silo conveyors to the silo loading opening with a certain linear velocity. That is, the grain falling onto the concrete bottom already has some initial velocity, and this should be taken into account when determining the impact force.

Inside the silo, individual kernels of the grain bulk move downward with uniform acceleration. The time during which an individual kernel passes through the silo height and strikes its bottom [98] is determined by the formula:

$$t = (-v_n + \sqrt{v_n^2 + 2 \cdot g \cdot H_c})/g, \quad (3.50)$$

where v_n is the initial velocity of the kernel after it leaves the conveyor and enters the silo loading opening; H_c is the internal height of the silo (the kernel falling height).

The velocity of uniformly accelerated motion at the moment of point impact of the kernel with the silo base is determined by the well-known formula:

$$v_{imp} = v_n + gt. \quad (3.51)$$

Substituting (3.50) into (3.51), we obtain the actual impact velocity, which does not explicitly include the falling time of the kernel:

$$\vartheta_{imp} = \sqrt{\vartheta_n^2 + 2gH_c} \quad (3.52)$$

Theoretical studies of the impact interaction of falling grain with the rigid concrete base of a silo were carried out using the theorem on the linear momentum of a material point, according to which it is not the force itself but the impulse of the force that imparts velocity to the kernel [99]. In turn, the velocity depends not only on the force impulse, but also on the mass and falling height.

Since the concrete bottom of the silo is not a smooth horizontal surface, but rather a rigid surface with small depressions and protrusions, the impact of the kernel should be considered oblique. In the analysis of the oblique impact of a kernel against a rigid surface, Routh's hypothesis is used [93].

3.6.2 Determination of the Impact Interaction of a Wheat Kernel with a Rigid Silo Base

According to the presented scheme, the velocity of the kernel at the beginning of impact is ϑ_{imp} (Equation 3.52), and at the end of impact it is u . This elementary time interval is divided into two stages.

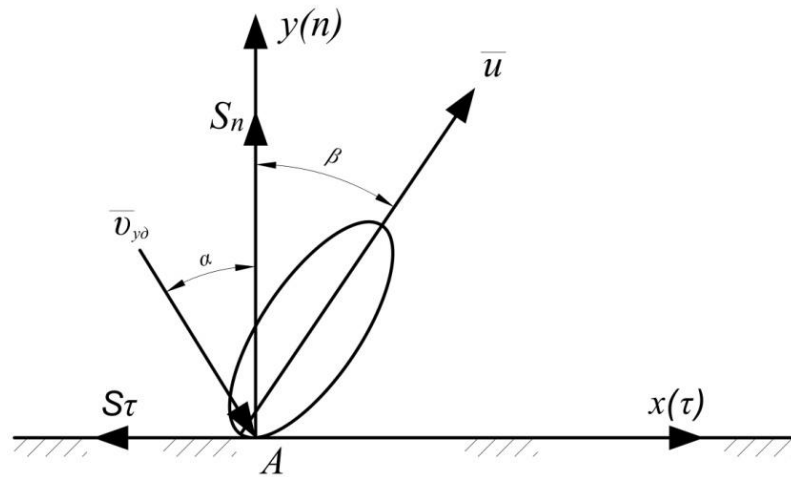


Figure 3.8 – Diagram of the interaction of falling winter wheat grain with a stationary rigid surface.

The first stage is characterized by a change in the shape and state of the impacting body. In this case, the normal component of velocity ϑ_{imp}^n changes from its maximum value to zero. Let the duration of this impact stage be denoted by t_1 . At this stage, local

deformation occurs at point A. The magnitude of deformation depends on the falling velocity of the kernel and the internal height of the silo. The greater the velocity and height, the more significant the consequences of grain damage resulting from its impact with the rigid concrete surface [98, 100].

At the second stage, the original shape of the kernel is restored due to its elastic-plastic properties. The initial shape of the kernel is restored provided that it was not damaged during the first stage of deformation. Let the time required for restoring the original shape of the kernel be denoted by t_2 . At this stage, the normal component of the rebound velocity increases from zero to its final value.

Let us consider the coordinate system AXY , the origin of which is located at point A, where the kernel comes into contact with the concrete base of the silo. We determine the velocity vectors of the kernel using the unit vectors n and τ .

The velocity at the moment of impact t is:

$$\bar{v}_{imp} = v_{\tau} \bar{\tau} + v_n \bar{n}.$$

The velocity at the end of kernel deformation, when $u_n=0$, at time $t+t_1$, is:

$$\bar{u} = u_{\tau} \bar{\tau}.$$

The velocity at the end of impact, at time $t + t_1 + t_2$:

$$\bar{u}_{reb} = u_{\tau} \bar{\tau} + u_n \bar{n}.$$

Each of the above stages corresponds to its own impact impulse. During time t_1 , the deformation impact impulse S_1 of the kernel occurs, and its vector is directed along the AY axis (along the normal nnn) vertically upward. During time t_2 , the recovery impact impulse S_2 occurs, which is also directed along the normal to the silo base.

The total vector impact impulse of the kernel against the concrete base of the silo is:

$$\bar{S}_{tot} = \bar{S}_1 + \bar{S}_2. \quad (3.53)$$

Using Newton's second law in impulse form, which states that the change in the total momentum of a body is equal to the impulse of the force [101] acting on it, we obtain:

$$S_{tot} = \int_0^{H_c} F_{imp} dt = F_{imp} \cdot t_{imp}, \quad (3.54)$$

where t_{impt} is the instantaneous duration of the kernel impact against the concrete bottom of the silo.

On the other hand,

$$S_{\text{tot}} = m_k(u - v_{\text{imp}}) \quad (3.55)$$

Substituting (3.55) into (3.54) and performing some transformations, we determine the maximum force of contact interaction between the kernel and the concrete base of the silo during oblique impact:

$$F_{\text{imp}} = \frac{m_k(u - v_{\text{imp}})}{t_{\text{imp}}} = \frac{S_{\text{tot}}}{t_{\text{imp}}}. \quad (3.56)$$

Let us determine the instantaneous impact duration, which consists of the deformation time of the body and the time of its recovery. This time is very short, but it characterizes the impact interaction of the contacting bodies. In our problem, it can be determined using wave processes. It is known that when grain strikes the stationary concrete base of a silo, a sound impact wave v_{wave} is generated. Using the geometric characteristics of a winter wheat kernel and the duration of sound wave propagation in concrete, we determine the instantaneous impact time:

$$t_{\text{imp}} = \frac{d_{\text{imp}}}{2v_{\text{wave}}} = \frac{k_f(a \cdot b \cdot c)^{1/3}}{2v_{\text{wave}}}, \quad (3.57)$$

where $d_{\text{imp}} = k_f \sqrt[3]{a \cdot b \cdot c}$ is the equivalent diameter of a winter wheat kernel; k_f is the coefficient that takes into account the kernel shape (for wheat grain, $k_f = 1$ [95]); a , b , and c are respectively the length, width, and thickness of the winter wheat grain, in meters. On average, for wheat, the equivalent diameter is about 3.0 to 4.5 mm, depending on the variety and moisture content of the grain.

The coefficient k_f accounts for the actual geometric shape of the wheat seed relative to an ideal spherical body.

Under real conditions, the impact impulse is unknown both in magnitude and in direction. To determine the maximum impact force of a kernel of mass m_k against the concrete base of the silo, we use the well-known Routh hypothesis [93]. According to

this hypothesis, the tangential and normal components of the impact impulses are related to each other by the coefficient of sliding impact friction:

$$S_\tau = f_d S_n, \text{ also } S_x = f_d S_y, \quad (3.58)$$

where f_d is the coefficient of sliding impact friction, determined experimentally.

Let us project the velocities ϑ_{imp} and u onto the coordinate axes AX and AY.

For axis AX:

$$\vartheta_{imp}^x = \vartheta_{imp} \sin \alpha; u^x = u \cdot \sin \beta.$$

For axis AY:

$$\vartheta_{imp}^y = \vartheta_{imp} \cos \alpha; u^y = u \cos \beta.$$

Using Equation (3.56), we determine the impact impulses along the corresponding coordinate axes. The impact impulses along axes AX and AY are:

$$\begin{cases} m_H(u^x - \vartheta_{yA}^x) = -S_x \\ m_H(u^y + \vartheta_{yA}^y) = +S_y \end{cases} \quad (3.59)$$

The coefficient of restitution for the oblique impact of a kernel against the concrete base can be expressed as:

$$K_r = \frac{u_{imp}^y}{\vartheta_{imp}^y} \quad (3.60)$$

Then the impact impulse along the AYAYAY axis, taking into account (3.60), will be:

$$S_y = m_k \vartheta_{imp}^y (1 + K_r). \quad (3.61)$$

Or

$$S_y = m_k \vartheta_{imp} (1 + K_r) \cos \alpha. \quad (3.62)$$

The impact impulse along the AX axis using (3.58) will be:

$$S_x = f_d S_y = m_k \vartheta_{imp} f_d (1 + K_r) \cos \alpha \quad (3.63)$$

The total impact impulse during the collision of the kernel with the concrete bottom of the silo can be represented as:

$$S_{tot} = \sqrt{S_x^2 + S_y^2} = m_k \vartheta_{imp} (1 + K_r) \cos \alpha \sqrt{1 + f_d^2} \quad (3.64)$$

Substituting (3.52), (3.57), and (3.64) into (3.56), we obtain the relation for determining the impact force of a kernel against the concrete bottom of the silo during oblique impact:

$$F_{imp} = \frac{m_k \sqrt{v_n^2 + 2gH_c} v_{wave} (1 + K_r) \cos \alpha \sqrt{1 + f_d^2}}{2K_f \sqrt[3]{a \cdot b \cdot c}}. \quad (3.65)$$

During the contact interaction of a winter wheat grain with the rigid concrete bottom of the silo at an angle α to the normal, internal stresses arise in the grain, which lead to its damage.

3.6.3 Calculation of the Impact Force Magnitude

For the calculations, the following average data were selected for winter wheat grain and a silo mounted on a concrete base. The constant values used in the calculations were: $m_k = 4 \cdot 10^{-5}$; $v_n = 0.68$ m/s; $H_c = 26.27$; $v_{wave} = 4000$ m/s; $a = 7$ mm; $b = 2.5$ mm; $c = 3$ mm; $g = 9.81$ m/s². After performing calculations to determine the impact force for the fixed values $\alpha = 20^\circ$ and $K_r = 0.41$, it was established that the impact force is a function of the coefficient of impact sliding friction ($F_{imp} = \varphi(f_d)$). By substituting the constant average data and the fixed values into Equation (3.65), while varying the coefficient of impact sliding friction, the values of the impact force during the fall of a grain kernel onto the silo bottom were obtained. This functional relationship is shown in Fig. 3.9.

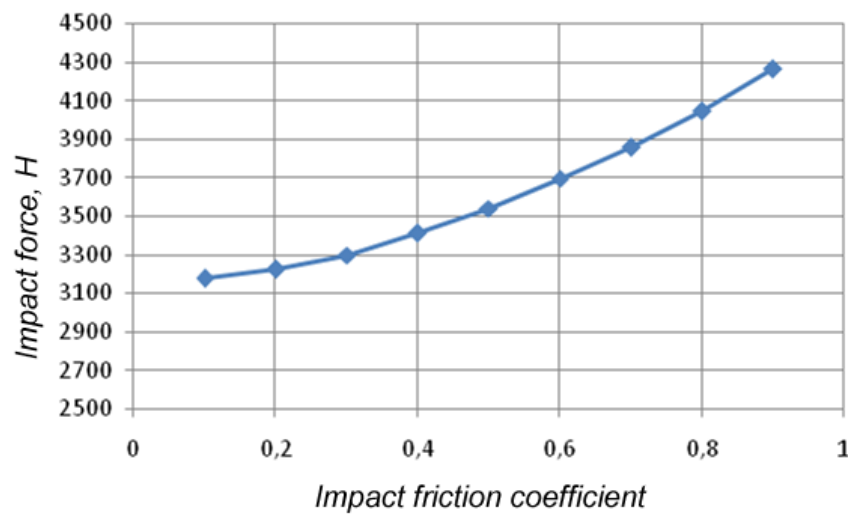


Figure 3.9 – Dependence of the impact force of a winter wheat kernel against the concrete bottom of a silo on the coefficient of impact sliding friction at $\alpha=20^\circ$ and $K_r=0.41$.

The graph shows that the impact force depends on the coefficient of impact friction. As f_d increases, the impact force also increases. This occurs as a result of a longer interaction of the kernel with the concrete bottom of the silo, which is caused by sliding friction.

In the oblique impact of a winter wheat kernel against the concrete bottom of a silo, the normal and tangential components of the impact impulses are related to each other by the coefficient of impact sliding friction. The magnitude of the impact force depends on the velocity and height of kernel fall, as well as on the physical and mechanical properties of the concrete silo bottom and the geometric dimensions of the kernel.

3.7 Compressive Damage to Grain in Silos

Loading of cylindrical containers (silo type) occurs by free falling of grain material from a considerable height. The nature of grain movement inside the container is influenced by the shape of the loaded grain and its roughness. When grain falls into the container, a conical heap is formed (Fig. 3.10).

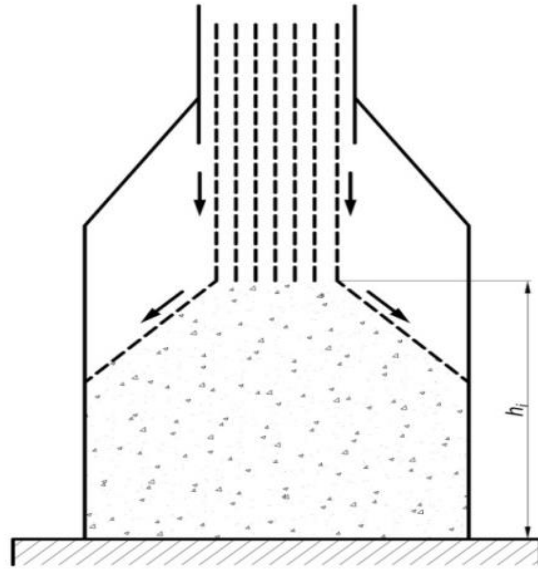


Figure 3.10 – Diagram of grain loading into a silo

As grain material enters the container, the height of the heap (h) increases. Dynamic forces arise in the formed grain heap, leading to compressive damage to the grain. In addition, the grain bulk presses on the silo base and simultaneously on its cylindrical shell. The action of static pressure on the silo base was described in [102, 103], and the distribution of stresses arising in silos was considered in [104].

Static pressure is generally characteristic of the lower layers of the grain heap. The magnitude of the dynamic force is determined by:

$$F_g = q \cdot v_k = q \cdot \sqrt{\frac{2mg}{c_x \cdot \rho_n \cdot S}}, \quad (3.66)$$

where q – feed rate of grain material; v_k – grain velocity at the moment it contacts the grain heap; ρ_n – density of the air medium in the silo; c_x – dimensionless drag coefficient depending on the shape of the grain bulk; S – mid-section area of the grain; m – grain mass.

Under the action of the dynamic force, the grain heap becomes compacted. As the container is filled with grain, the dynamic (compressive) forces increase. After the container has been completely filled with grain, these dynamic forces become somewhat stabilized, and this leads to further grain damage and caking. It is known that caking negatively affects the stable discharge of grain material from the container.

The loose grain material loaded into a cylindrical container is a two-phase dispersed system. This system is characterized by bulk density, density of the solid part of the grain bulk, and a compaction coefficient. As is known, the value of this coefficient depends on the conditions under which the grain heap is formed inside the cylindrical container. Table 2.1 presents the values of the compaction coefficient for the main agricultural crops [90].

The compaction coefficient depends on the height of the grain heap layer and can be determined by the formula:

$$K_y = a \cdot K_{\max} \left[1 - e^{-(b - ch_i)} \right], \quad (3.67)$$

where a , b , c – are constant coefficients (for wheat: $a=1$; $b=1.6$; $c=0.332$); h_i – height of the grain layer in the heap.

The phenomenon of caking is the adhesion of individual grain particles in the grain heap. When the container is loaded unevenly with grain, dynamic loads accelerate the caking process, which negatively affects the quality indicators of the grain.

Compaction of the grain heap in the container is accompanied by friction of individual kernels against one another. In this case, thermal energy is generated and dissipated inside the container.

During gravitational loading of containers with grain in a compact stream, segregation of the grain bulk occurs, and this continues on the grain heap itself. That is, the grain flow is separated into light and heavy particles. Segregation leads to an increase in compressive damage to the grain, especially in places where heavier particles of the grain bulk accumulate.

Let us consider the dynamics of load distribution in a container completely filled with grain (Fig. 3.11). For this purpose, an elementary grain volume of height dh is selected at an arbitrary location. The selected elementary volume is acted upon by: the weight force G , the pressure p of the grain bulk located above the selected elementary volume, the reaction of the lower grain layer, and the reaction from the container wall.

If the selected elementary volume is in static equilibrium, then the sum of all forces acting on it is equal to zero:

$$G + ps + R_i \cdot S + R_c = 0, \quad (3.68)$$

where $G = s \cdot dh \cdot \rho_e \cdot g$ – weight of the selected elementary grain volume;

S – area of the selected grain layer;

$$R_c = p \cdot \varepsilon \cdot L \cdot dh.$$

After substitution of the physical and mechanical parameters of the grain bulk, Equation (3.68) takes the following form:

$$\frac{\gamma}{K_y} \cdot S \cdot g \cdot dh + PS - (p + ds)S - P\varepsilon \cdot L \cdot dh = 0, \quad (3.69)$$

where γ – bulk density of the selected grain volume;

K_y – compaction coefficient of the grain heap;

$\varepsilon = \xi_{\sigma} \cdot f_T$ – complex coefficient;

L – circumference of the selected grain layer;

ξ_{σ} – lateral pressure coefficient;

f_T – friction coefficient.

After simplification, Equation (3.69) takes the following form:

$$\frac{dp}{dh} = \left(1 - \frac{P \cdot \varepsilon \cdot K_y}{R_r \cdot \gamma \cdot g} \right) \frac{\gamma \cdot g}{K_y}, \quad (3.70)$$

where $R_r = \frac{S}{L}$ is the hydraulic radius of the cross-section of the container.

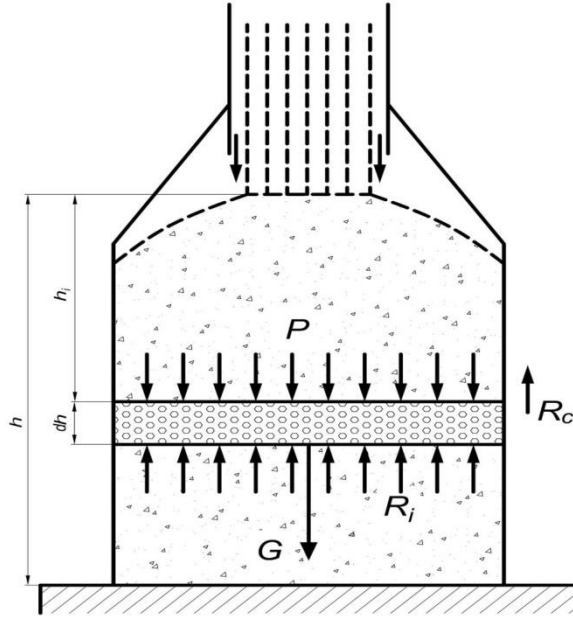


Figure 3.11 – Dynamics of distribution of static loads in a silo

For the simplified solution of Equation (3.70), the following notation was introduced:

$$b = \frac{\varepsilon \cdot K_y}{R_r \cdot \gamma \cdot g}; a = \frac{\gamma \cdot g}{K_y} \quad (3.71)$$

Equation (3.70), taking into account notation (3.71), takes the following form:

$$\frac{dp}{dh} = (1 - p \cdot b) \cdot a,$$

and after separation of variables the equation is integrated:

$$\frac{dp}{(1 - p \cdot b)} = a \cdot dh. \quad (3.72)$$

After integration of the obtained expression, we have:

$$p \cdot b = 1 - e^{-b \cdot (a \cdot h + c)}$$

Assume that on the surface of the selected elementary volume ($h=0$) the pressure forces are absent, that is, $p=0$, then

$$p = \frac{1 - e^{-a \cdot b \cdot h}}{b} . \quad (3.73)$$

After substituting (3.71) into (3.73), we obtain the relationship for determining the pressure of the grain bulk located in the cylindrical silo container:

$$p = \frac{\left(1 - e^{-\frac{\varepsilon \cdot h}{R_r}}\right) R_r \cdot \gamma \cdot g}{\varepsilon \cdot K_y} . \quad (3.74)$$

Let us consider a dry grain storage silo of model 2215/15 manufactured by Symaga S.A. It is a cylindrical steel container installed on a flat concrete base. The silo diameter is 22.15 m and its height is 17.1 m.

When storing dry corn grain in this silo, the following characteristics are assumed: specific weight $\gamma=800 \text{ kg/m}^3$, internal friction angle $\varphi=25^\circ$, and coefficient of friction on metal $f=0.4$.

The lateral pressure coefficient is:

$$\xi_\sigma = \operatorname{tg}^2\left(45^\circ - \frac{\varphi}{2}\right) = \operatorname{tg}^2\left(45^\circ - \frac{25^\circ}{2}\right) = 0,406.$$

The hydraulic radius of the silo cross-section is:

$$R_r = \frac{S}{L} = \frac{\pi \cdot d^2}{4 \cdot \pi \cdot d} = \frac{22,15}{4} = 5,54 \text{ m}.$$

The walls of the silo manufactured by Symaga S.A. are made of corrugated profile sheets; therefore, the coefficient of friction should be taken not as grain-on-metal

friction, but as corn-on-corn friction. Thus, the coefficient of friction of corn grain against corn grain is:

$$f = \operatorname{tg} 25^{\circ} = 0,47.$$

By substituting the main parameters of corn grain and the geometric parameters of the silo into Equation (3.58), we obtain:

For corn grain

$$p_{\kappa} = 387,1 \cdot (1 - e^{-0,035 \cdot h}),$$

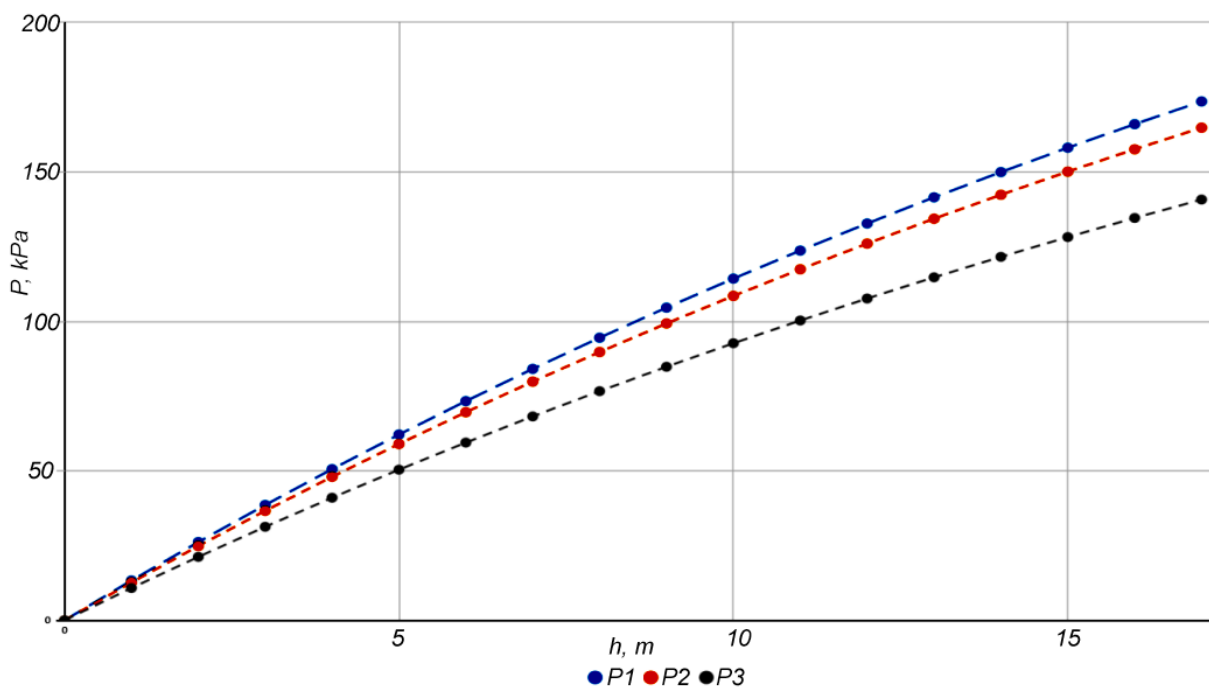
For wheat grain

$$p_n = 367,5 \cdot (1 - e^{-0,035 \cdot h}),$$

For barley grain

$$p_{\pi} = 313,9 \cdot (1 - e^{-0,035 \cdot h}).$$

Figure 3.12 shows the graph of pressure changes of corn, wheat, and barley grain bulk in a silo manufactured by Symaga S.A. depending on the filling height.



P1 – corn; P2 – wheat; P3 – barley.

Figure 3.12 – Dependence of pressure variation on the filling height of the container with grain bulk in a silo manufactured by Symaga S.A.

Figure 3.12 shows that the pressure of the bulk grain changes over the entire silo height according to a logarithmic curve. To reduce this load, the ratio of silo height to diameter should be within the limits $0.65 < h/d < 1.6$, where h is the height of the cylindrical part of the silo, and d is the silo diameter.

All metal silos, depending on the load on the bottom, are divided into three groups. For the first group of silos, the load on the bottom should not exceed 120 kPa [105]. This is typical of relatively small silos with a diameter of 11–16 m and a height of 11–18.7 m, that is, with a ratio $h/d=0.75–1.6$.

The second group includes silos in which the force load on the bottom ranges from 120 to 160 kPa, and the third group includes silos in which the force load on the bottom exceeds 160 kPa.

The ratio of silo height to diameter has a significant effect on the redistribution of grain loads on the walls and bottom of metal silos made of corrugated panels. Figure 3.13 shows the geometric parameters of a metal silo and the loads acting on the bottom when the silo is fully loaded with grain material. The vertical pressure on the flat concrete bottom is determined by the formula [105]:

$$P_{3ar} = P_1 + \Delta P_2 \left(\frac{2,0 - h_c/d_c}{2,0 - h_{hc}/d_c} \right), \quad (3.75)$$

where ΔP_2 is the difference between vertical pressures determined by two methods for a hopper of low flexibility; P_1 is the vertical pressure at the base level of a hopper of low flexibility; h_{hc} is the total height of the bulk cone on the surface of the loose material; h_c is the height of the vertical shaft of the hopper from the transition unit to the equivalent surface of the loose material; d_c is the internal diameter of the silo.

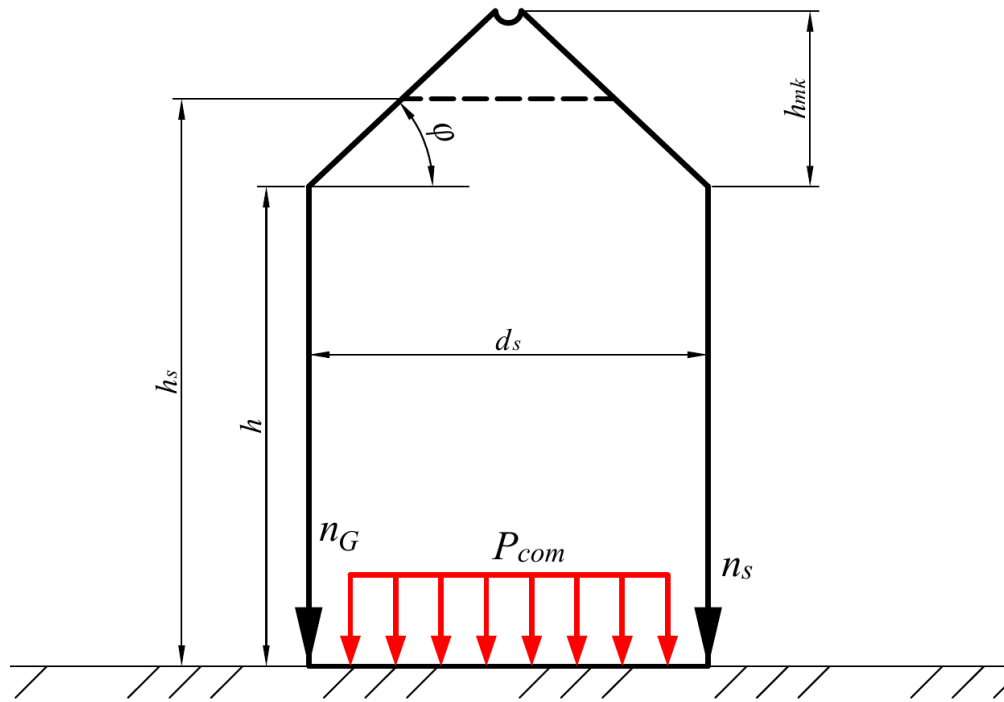


Figure 3.13 – Geometric parameters of the silo and the loads acting on the silo bottom

To reduce compressive damage to grain in the lower layers of the heap and other undesirable phenomena, special devices are used, an overview of which is given in the second chapter of the work. The considered technical means for gentle loading of containers with grain make it possible to distribute the grain bulk uniformly over the entire area of the container, which in turn leads to a reduction in compressive damage to the grain.

CHAPTER 4. THEORETICAL JUSTIFICATION OF THE OPERATION OF DEVICES FOR GENTLE LOADING OF GRAIN INTO SILOS

4.1 General Provisions on Gravitational Motion During Filling of Silos with Grain Material

Modern silo structures are generally filled with grain material in a compact stream, while a certain percentage of damaged grain accumulates in the lower layers of the grain heap. Such grain settles intensively, which in turn leads to compaction of the grain material and its compression. Papers [21, 24, 93, 106–112] present generalized material currently available on the issue of rapid gravitational flows of grain materials in chutes and channels of various designs, on inclined planes, and so forth. As indicated in the above-mentioned works, gravitational flows of grain materials are accompanied by segregation effects and possible damage to grain kernels. When silos are loaded in a compact stream, segregation of the grain heap is observed [120]. It significantly affects the dynamics of grain bulk motion.

The conducted literature analysis indicates that both domestic and foreign researchers [113–119] have studied theoretical issues related to the gravitational movement of grain material along various working elements. These studies indicate that a fundamental feature of rapid gravitational flows is the chaotic movement of grain material with a considerable linear velocity. Such flows are accompanied by active interaction of the bulk particles both with one another and with the working elements, as a result of which such side effects as mixing and separation may occur. This negatively affects the entire technological process associated with loading grain into silos and its long-term storage.

As noted earlier, in order to reduce the delivery velocity of the grain mass to the silo bottom without damaging it, special devices should be used. Thus, in studies [50, 51, 55], it is proposed that, in order to reduce the velocity of gravitational falling of the grain bulk below the silo loading opening, a gravitational distributor should be installed. When the grain bulk reaches the lateral surface of this device, its gravitational vertical velocity changes to a velocity directed at an angle to the horizontal. As a result of such

a change in velocities, the grain material is damaged less and the dynamic compaction of the grain heap decreases.

When silos are loaded using vertical screw conveyors, the grain bulk performs a helical motion. Studies [3, 24, 74, 78] present theoretical investigations of the gravitational movement of grain kernels along a helical surface. Such motion makes it possible to reduce the delivery velocity of the grain material into the silo. A disadvantage of this loading method is the presence of a bulky cascade structure inside the cavity of the container.

To eliminate this drawback, it is necessary to install a peripheral open helical channel (POHC) with variable inclination angles to the horizontal inside the silo. Its design and operating principle are described in Chapter 2 of this work.

4.2 Mathematical Modeling of Grain Motion in a Spiral Helical Channel

4.2.1 Justification of Grain Material Motion in an Open Helical Channel

To reduce grain damage, a peripheral open helical loading device (POHC) with variable descent angles may be used (Fig. 2.21). The loading device consists of an accelerating section and a helical braking section, which are installed at different angles to the horizontal. The POHC is attached to the inner part of the silo with the possibility of adjusting the descent angles. As the silo is filled with grain, the grain is discharged into the open helical channel.

At the beginning of its motion along the helical surface, the grain flow has a certain potential energy, which under the action of gravity is converted into kinetic energy, while a small part of it is spent on heating the working surface of the helical channel. Subsequently, the thermal energy is dissipated inside the silo. Most of the kinetic energy of the moving grain flow is used for loading the silo with grain.

For normal motion of the grain flow along the trough of the helical surface, the angle in the upper part of the POHC must be greater than the angle of repose [78]. Such a condition ensures the formation of a stable grain flow along the working surface of the helical channel. After passing the first section of the helical channel with pitch, the

velocity of the grain flow decreases due to a decrease in the angle. Upon reaching the final descent section, the grain flow is smoothly discharged into the lower part of the container, uniformly filling its entire volume. In this case, the exit velocity of the grain from the braking channel is fully reduced due to a decrease in the descent angle from the initial value to the final one. A smooth decrease in the descent angle prevents the occurrence of critical values of impact forces of grain against the walls and bottom of the container, which in turn reduces the probability of mechanical grain damage. As the silo is filled with grain, the helical channel is also gradually filled.

The use of a helical channel in cylindrical grain storage containers contributes to the creation of the velocity gradient required for the technological process over the entire path of grain flow motion. The velocity gradient created by this device ensures unobstructed and rapid movement of the grain flow in the upper part of the helical channel and its deceleration in the lower parts of the device. Such a design of the working element minimizes deformation failure of grain and significantly reduces the level of grain damage.

To describe the process of grain flow motion along the open helical channel, taking into account the interaction of grain with the material from which the trough of the helical channel is made, let us formulate the system of forces acting on an elementary volume of grain material.

4.2.2 System of Forces Acting on an Elementary Volume of Grain Flow in an Open Helical Channel

Silo containers are generally loaded with grain material by the gravitational method. That is, grain material is conveyed to the silo throat by conveyors and discharged downward into the container. Falling grain, especially during the initial period of loading, strikes the concrete bottom of the structure and becomes damaged. As a result, damaged grain accumulates in the lower part of the silo.

To eliminate this drawback, a spiral helical device with different descent angles can be used. The spiral helical loading device has several different helical sections. The first helical section is an accelerating one with an angle α_1 to the horizontal. The

subsequent sections are braking sections with angles smaller than α_1 . If the device consists of two braking sections, which depends on the silo height, then $\alpha_1 > \alpha_2 > \alpha_3$ [78].

The spiral helical loading device is mounted on the inner cylindrical part of the silo. It is made of a U-shaped profile, the open part of which is directed upward, and has accelerating and braking sections with corresponding variable inclination angles.

During the movement of grain material in the spiral helical channel, a certain system of forces acts on an elementary grain volume. In this regard, a mathematical model of the forces acting on an elementary volume of grain flow in the helical channel was developed using a cylindrical coordinate system (Fig. 4.1).

The gravitational movement of the grain mass along the helical channel occurs under the action of the driving force, which is determined from the balance of forces acting on the selected moving mass:

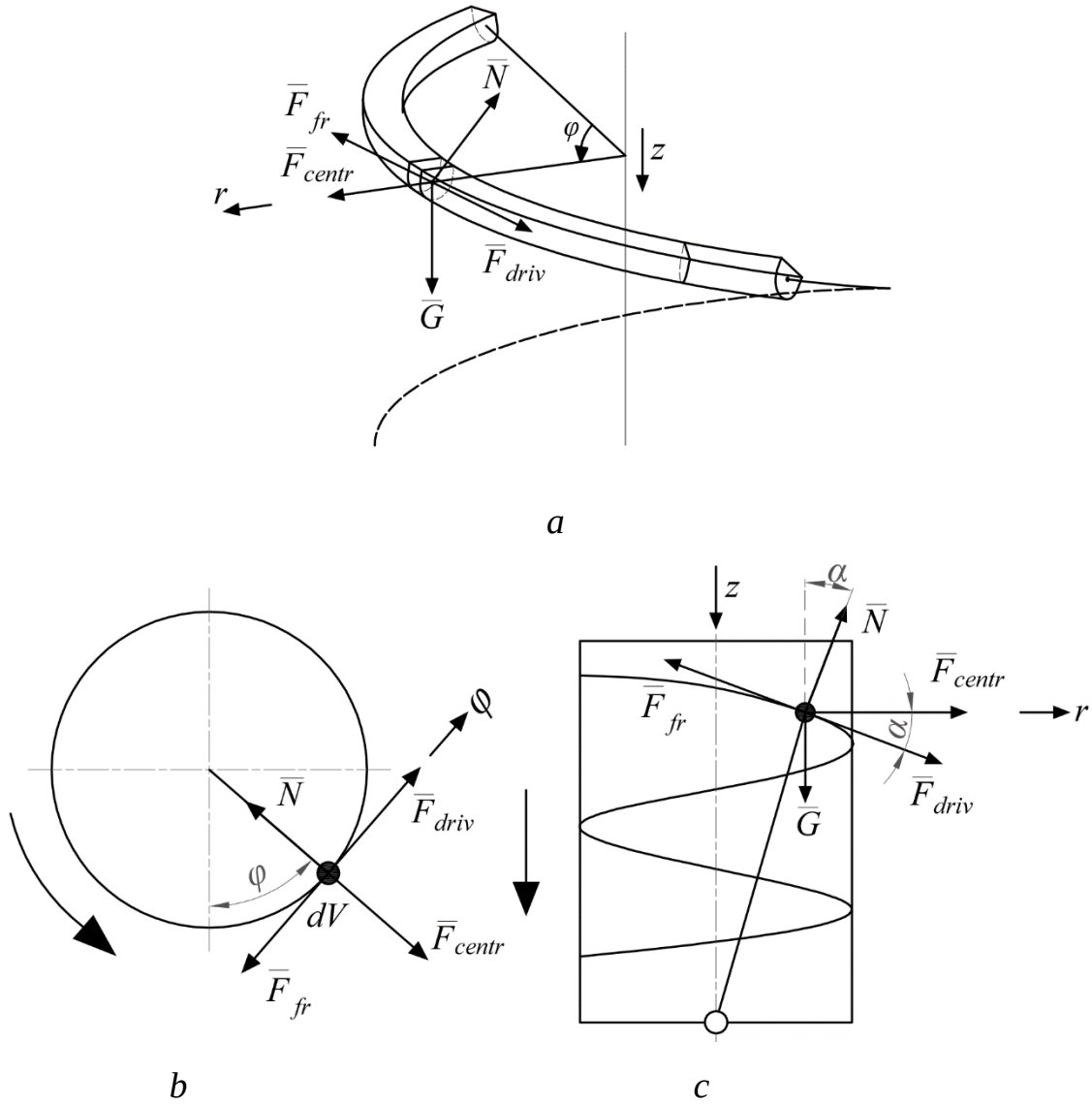
$$\vec{F}_{pyu} = \sum \vec{F}_k \text{ a6o } m\vec{a} = \sum \vec{F}_k, \quad (4.1)$$

where $\sum \vec{F}_k$ – is the sum of all forces acting on the selected mass of grain flow in the helical channel.

Taking into account the rotational-translational nature of grain motion in the helical channel, the force balance in vector form is as follows [78]:

$$m\vec{a} = \vec{F}_{mepm} + \vec{F}_{\text{ciou}} + \vec{N} + \vec{G}, \quad (4.2)$$

where $\vec{F}_{mepm}$ – is the friction force of the grain flow against the surface of the helical channel; $\vec{F}_{\text{ciou}}$ – is the centrifugal force acting on the grain flow during its rotational motion around the central axis of the helical channel; $\vec{N}$ – is the normal reaction force of the helical channel surface; $\vec{G}$ – is the gravitational force.



a – spatial representation; b – horizontal representation; c – vertical representation.

Figure 4.1 – System of forces acting on an elementary volume of grain flow in the helical channel in a cylindrical coordinate system

By projecting all force components onto the corresponding directions of the cylindrical coordinate system, the force balance can be represented as the following system of force projections:

$$\begin{cases} ma_r = F_{\text{sidy}}^r - N^r, \\ ma_\varphi = -F_{\text{mepm}}^\varphi + N^\varphi, \\ ma_z = -F_{\text{mepm}}^z - N^z + G^z, \end{cases} \quad (4.3)$$

where a_r , a_φ , a_z – are the projections of the acceleration of the grain mass mmm

in the radial, angular, and vertical directions of the cylindrical coordinate system; $F_{sid\varphi}^r$, N^r – are the projections of the centrifugal force and the normal reaction force in the radial direction;; F_{mepm}^φ , N^φ – are the projections of the friction force and the normal reaction force in the angular direction;; F_{mepm}^z , N^z , G^z – are the projections of the friction force, the normal reaction force, and the gravitational force in the vertical direction.

4.2.3 Justification of the Theoretical Model of Grain Velocity in an Open Helical Channel

The projections of the acceleration vector in system (4.3) along each direction of the cylindrical coordinate system, taking into account the absence of grain mass motion in the radial direction, are determined from the following expressions:

$$\begin{cases} a_r = 0, \\ a_\varphi = r \cdot \frac{d^2\varphi}{dt^2} + 2 \frac{dr}{dt} \frac{d\varphi}{dt}, \\ a_z = \frac{d^2z}{dt^2}. \end{cases} \quad (4.4)$$

Since there is no displacement of the grain mass in the radial direction, the coordinate r takes a constant value, and the component in system of equations (4.4) becomes zero. Therefore, this system takes the following form:

$$\begin{cases} a_r = 0, \\ a_\varphi = r \cdot \frac{d^2\varphi}{dt^2}, \\ a_z = \frac{d^2z}{dt^2}. \end{cases} \quad (4.5)$$

Taking into account the zero radial acceleration $a_r=0$, system of equations (4.3) is simplified as follows:

$$\begin{cases} F_{\text{oidy}}^r = N^r, \\ ma_{\varphi} = -F_{\text{mepm}}^{\varphi} + N^{\varphi}, \\ mv_z = -F_{\text{mepm}}^z - N^z + G^z. \end{cases} \quad (4.6)$$

The centrifugal force acting on the grain mass during its rotation about the axis of the helical channel is determined from the expression:

$$F_{\text{oidy}} = mr\omega^2, \quad (4.7)$$

where r is the distance from the axis of the helical channel to the center of gravity of the grain mass; ω is the angular velocity of rotation of the grain mass.

The friction force F_{fr} is:

$$F_{\text{mepm}} = \mu \cdot N, \quad (4.8)$$

where μ is the coefficient of friction of the grain against the surface of the helical channel, and N is the normal reaction force.

Taking into account relations (4.7) and (4.8), system of equations (4.6) takes the following form:

$$\begin{cases} N^r = mr\omega^2, \\ ma_{\varphi} = -\mu N^{\phi} \cos \alpha + N^{\phi}, \\ ma_z = -\mu N^z \sin \alpha - N^z + mg. \end{cases} \quad (4.9)$$

After factoring out common terms and grouping them, system (4.9)

becomes:

$$\begin{cases} N^r = mr\omega^2, \\ ma_{\varphi} = N^{\phi} (1 - \mu \cos \alpha), \\ mv_z = mg - N^z (1 + \mu \sin \alpha). \end{cases} \quad (4.10)$$

The projections of the normal reaction force, N_φ and N_z can be found by projecting them onto the direction of the gravitational force (Fig. 4.1):

$$\begin{cases} N_\varphi = G \sin \alpha, \\ N_z = G \cos \alpha, \end{cases} \text{ also } \begin{cases} N_\varphi = mg \sin \alpha, \\ N_z = mg \cos \alpha, \end{cases} \quad (4.11)$$

where α – is the inclination angle of the helical line at a given section of the gravitational channel.

Taking into account expressions (4.11), system (4.10) takes the following form:

$$\begin{cases} N^r = mr\omega^2, \\ ma_\varphi = (1 - \mu \cos \alpha) \cdot mg \cdot \sin \alpha, \\ ma_z = mg - (1 + \mu \sin \alpha) \cdot mg \cdot \cos \alpha. \end{cases} \quad (4.12)$$

After simplification and trigonometric transformations, we obtain:

$$\begin{cases} N^r = mr\omega^2, \\ a_\varphi = g \cdot (\sin \alpha - 0.5 \cdot \mu \sin 2\alpha), \\ a_z = g(1 - \cos \alpha - 0.5\mu \sin 2\alpha). \end{cases} \quad (4.13)$$

By substituting the acceleration projections a_φ and a_z with their expressions from system of equations (4.5), system (4.13) is written as follows:

$$\begin{cases} N^r = mr\omega^2, \\ r \frac{d^2\varphi}{dt^2} = g(\sin \alpha - 0.5 \cdot \mu \sin 2\alpha), \\ \frac{d^2z}{dt^2} = g(1 - \cos \alpha - 0.5\mu \sin 2\alpha). \end{cases} \quad (4.14)$$

After making the following substitution:

$$\begin{aligned} K_1 &= \frac{1}{r} g(\sin \alpha - 0.5 \cdot \mu \sin 2\alpha), \\ K_2 &= g(1 - \cos \alpha - 0.5 \mu \sin 2\alpha). \end{aligned} \quad (4.15)$$

system (4.13) is reduced to the following form:

$$\begin{cases} N^r = mr\omega^2, \\ \frac{d^2\varphi}{dt^2} = K_1, \\ \frac{d^2z}{dt^2} = K_2. \end{cases} \quad (4.16)$$

To find an analytical solution of the obtained system of differential equations, double integration was performed:

$$\begin{cases} N^r = mr\omega^2, \\ \frac{d\varphi}{dt} = K_1 t + C_1, \\ \frac{dz}{dt} = K_2 t + C_3, \end{cases} \quad (4.17)$$

$$\begin{cases} N^r = mr\omega^2, \\ \varphi = 0.5 K_1 t^2 + C_1 t + C_2, \\ z = 0.5 K_2 t^2 + C_3 t + C_4. \end{cases} \quad (4.18)$$

The obtained integration constants C_1 , C_2 , C_3 and C_4 are determined taking into account the corresponding boundary conditions.

The total path traveled by the grain mass along the helical channel, taking into account the character of variation of the coordinates φ and z according to system of equations (4.18), is determined from the expression:

$$l = \sqrt{(r \cdot \varphi)^2 + z^2}. \quad (4.19)$$

The velocity V of grain mass motion, taking into account $V = \frac{d\ell}{dt}$, is determined as:

$$V = \frac{r^2 \varphi(t) \frac{d}{dt} \varphi(t) + z(t) \frac{d}{dt} z(t)}{\sqrt{r^2 (\varphi(t))^2 + (z(t))^2}}. \quad (4.20)$$

If the helical device has a single spiral inclination angle α , then the channel has no braking section, and the grain mass continuously increases its velocity. That is, according to (4.20), we obtain the grain motion velocity only for the accelerating section:

$$V = \frac{r^2 \varphi^p(t) \frac{d}{dt} \varphi^p(t) + z^p(t) \frac{d}{dt} z^p(t)}{\sqrt{r^2 (\varphi^p(t))^2 + (z^p(t))^2}}. \quad (4.21)$$

To prevent grain damage, it is necessary that the velocity of the grain mass during silo loading should not increase significantly. For this purpose, the presented theoretical helical unit (Fig. 4.1) should be improved and conditionally divided into an accelerating section and a braking section, with spiral lengths l_A and l_B and inclination angles to the horizontal α and β , respectively. Thus, the grain velocity at the end of the accelerating section should be maximal, V_{max} . At the same time, the final grain velocity at the end of the braking section should be as small as possible, but not less than the initial grain mass velocity at the accelerating section, that is, $V_{init} \leq V_{fin}$ [78]. The latter condition ensures the passage of grain without its accumulation at any section of the device. For further investigation, it was assumed that these velocities are equal, $V_{init} = V_{fin}$ [78].

Let V_0 be the velocity acquired by grain under the action of gravity while falling from the bunker opening located at a height h_0 above the edge of the channel accelerating section. At the moment the grain falls from the bunker hopper onto the beginning of the trough, its potential energy is converted into kinetic energy, as a result of which the grain

acquires the velocity V_0 . According to the law of conservation of energy $mgh_0 = \frac{mV_0^2}{2}$ [121]. Therefore, the initial grain velocity is:

$$V_0 = \sqrt{2gh_0}. \quad (4.22)$$

Further investigation of grain motion velocity requires finding the mathematical relationship between the discretely varying inclination angles α and β of the spiral sections of the helical channel relative to the horizontal.

4.2.4 Determination of the Relationship Between the Inclination Angles of the Spirals in the Accelerating and Braking Sections of the Helical Channel

To obtain a formula that defines the mathematical relationship between the inclination angles of the accelerating and braking sections, α and β , under the condition $V_{\text{init}}=V_{\text{fin}}=V_0$, the results of previous studies [78] were used for the accelerating and braking sections, respectively. In addition to the friction force, the support reaction force, and the gravitational force, the centrifugal force acting on the grain with acceleration during its motion along the helical line was also taken into account. In accordance with the law of conservation of energy, a system of equations was developed to describe the transformation of kinetic and potential energy of the grain flow in the accelerating and braking sections of the cylindrical spiral:

$$\begin{cases} mgh_0 = \frac{mV_0^2}{2}, \\ \frac{mV_0^2}{2} + mgl_p \sin \alpha - \mu m \left(g + \frac{V^2}{r} \right) l_p \cos \alpha = \frac{mV_{\text{max}}^2}{2}, \\ \frac{mV_{\text{max}}^2}{2} + mgl_r \sin \beta - \mu m \left(g + \frac{V^2}{r} \right) l_r \cos \beta = \frac{mV_0^2}{2}. \end{cases} \quad (4.23)$$

By equating the second and third equations of system (4.23) and simplifying the

expression, we obtain:

$$\begin{aligned}
\frac{mV_0^2}{2} + mgl_p \sin \alpha - \mu m \left(g + \frac{V^2}{r} \right) l_p \cos \alpha + mgl_r \sin \beta - \mu m \left(g + \frac{V^2}{r} \right) l_r \cos \beta &= \frac{mV_0^2}{2}, \\
mgl_p \sin \alpha - \mu m \left(g + \frac{V^2}{r} \right) l_p \cos \alpha + mgl_r \sin \beta - \mu m \left(g + \frac{V^2}{r} \right) l_r \cos \beta &= 0, \\
l_p \sin \alpha - \mu \left(1 + \frac{V^2}{rg} \right) l_p \cos \alpha + l_r \sin \beta - \mu \left(1 + \frac{V^2}{rg} \right) l_r \cos \beta &= 0.
\end{aligned} \tag{4.24}$$

To simplify the further solution of (4.24), it was assumed that the lengths of the accelerating and braking sections are equal, that is, $l_A = l_B$.

Then:

$$\sin \alpha - \mu \left(1 + \frac{V^2}{rg} \right) \cos \alpha + \sin \beta - \mu \cos \beta = 0. \tag{4.25}$$

From equation (4.25), we obtain:

$$\begin{aligned}
\sin \alpha + \sin \beta &= \mu \left(1 + \frac{V^2}{rg} \right) \cos \alpha + \mu \left(1 + \frac{V^2}{rg} \right) \cos \beta, \\
\sin \frac{\alpha + \beta}{2} &= \mu \left(1 + \frac{V^2}{rg} \right) \cos \frac{\alpha + \beta}{2}, \\
\beta &= 2 \arctg \mu \left(1 + \frac{V^2}{rg} \right) - \alpha.
\end{aligned} \tag{4.26}$$

To simplify (4.26), it was assumed that the grain velocity V , which directly affects the centrifugal acceleration, is equal to V_0 . Then:

$$V = V_0 \rightarrow V^2 = V_0^2 = 2gh_0. \tag{4.27}$$

From (4.26), taking into account (4.27), the relationship between the angles of the accelerating and braking sections was finally determined:

$$\beta = 2 \arctg \mu \left(1 + \frac{2h_0}{r} \right) - \alpha. \quad (4.28)$$

4.2.5 Investigation of the Parameters of the Analytical Model of Grain Velocity in an Open Helical Channel with Two Variable Inclination Angles

Taking into account (4.28) and the results of studies [78], coefficients were also determined for the accelerating section (4.15) and for the braking part of the spiral with inclination angle β :

$$K_1^r = \frac{1}{r} g (\sin \beta - 0.5 \cdot \mu \sin 2\beta),$$

$$K_2^r = g (1 - \cos \beta - 0.5 \mu \sin 2\beta),$$

or

$$\begin{aligned} K_1^r &= \frac{1}{r} g \left(\sin \left(2 \arctg \mu \left(1 + \frac{2h_0}{r} \right) - \alpha \right) - 0.5 \cdot \mu \sin 2 \left(2 \arctg \mu \left(1 + \frac{2h_0}{r} \right) - \alpha \right) \right), \\ K_2^r &= g \left(1 - \cos \left(2 \arctg \mu \left(1 + \frac{2h_0}{r} \right) - \alpha \right) - 0.5 \mu \sin 2 \left(2 \arctg \mu \left(1 + \frac{2h_0}{r} \right) - \alpha \right) \right). \end{aligned} \quad (4.29)$$

Taking into account (4.29), system (4.18) was rewritten for the braking section in the following form:

$$\begin{cases} N^r = mr\omega^2, \\ \varphi^r = 0.5 K_1^r t^2 + C_1 t + C_2, \\ z^r = 0.5 K_2^r t^2 + C_3 t + C_4. \end{cases} \quad (4.30)$$

Using system of equations (4.30) and formula (4.20), the equation for the grain

mass velocity in the braking section of the helical channel was obtained:

$$v^r = \frac{r^2 \dot{\varphi}^r(t) \frac{d}{dt} \varphi^r(t) + z^r(t) \frac{d}{dt} z^r(t)}{\sqrt{r^2 (\dot{\varphi}^r(t))^2 + (z^r(t))^2}}. \quad (4.31)$$

For the further solution, the following facts were taken into account:

- in the accelerating section, the grain velocity increases from V_0 to $V_{\max}$ over the time interval $[0; t_p]$;
- in the braking section, the velocity begins to decrease and over the time interval $(t_p; t_{\max}]$ decreases to V_0 .

To derive an equation that would determine the instantaneous grain velocity at any moment of time in both sections, it is necessary to determine the time t_p . During this time, the grain passes from the accelerating section to the braking section, and the velocity reaches its maximum value.

Knowing the pitch of the accelerating section of the helical line, S , and the number of its turns, n_p , with inclination angle α , the height h_p of this section was first determined.

For this purpose, the length of one turn and the total length of the accelerating section, l_p , were determined:

$$\begin{aligned} S &= \pi dtg\alpha = 2\pi r tg\alpha, \\ l_0 &= \sqrt{(2\pi r)^2 + S^2} = \sqrt{4\pi^2 r^2 + (2\pi r tg\alpha)^2} = \sqrt{4\pi^2 r^2 + 4\pi^2 r^2 tg^2\alpha} = 2\pi r \sqrt{1 + tg^2\alpha}, \\ l_p &= n_p l_0 = n_p 2\pi r \sqrt{1 + tg^2\alpha}. \end{aligned} \quad (4.32)$$

On the other hand, by determining the pitch of one turn of the helical spiral, we obtain:

$$\begin{aligned} S &= \frac{h_p}{n_p}, \\ l_0 &= \sqrt{(2\pi r)^2 + \left(\frac{h_p}{n_p}\right)^2} = \sqrt{4\pi^2 r^2 + \left(\frac{h_p}{n_p}\right)^2}, \end{aligned}$$

$$l_p = n_p l_0 = n_p \sqrt{4\pi^2 r^2 + \frac{h_p^2}{n_p^2}} = \sqrt{4\pi^2 r^2 n_p^2 + h_p^2}. \quad (4.33)$$

Having found h_p , the right-hand sides of equations (4.32) and (4.33) were equated.

$$\begin{aligned} 2n_p \pi r \sqrt{1 + \operatorname{tg}^2 \alpha} &= \sqrt{4\pi^2 r^2 n_p^2 + h_p^2}, \\ h_p &= 2n_p \pi r \operatorname{tg} \alpha. \end{aligned}$$

Knowing h_p , the time of grain passage through the accelerating section, t_p , was determined. For this purpose, the equation $z(t)$ from system (4.18) was used, setting $z=h_p$:

$$\begin{aligned} z &= h_p = 0.5K_2 t^2 + C_3 t + C_4, \\ K_2 t^2 + 2C_3 t + 2C_4 - 2h_p &= 0, \\ t_{1,2} &= \frac{-2C_3 \pm 2\sqrt{C_3^2 - 2K_2(C_4 - h_p)}}{2K_2}, \\ t_p &= \frac{-C_3 + \sqrt{C_3^2 - 2K_2(C_4 - 2n_p \pi r \operatorname{tg} \alpha)}}{K_2}. \end{aligned} \quad (4.34)$$

The length of the device spiral consists of equal lengths of the accelerating and braking sections. From (4.19), the total length of the helical spiral corresponding to the adjacent sections was determined:

$$l = l_p + l_r = \sqrt{(r \cdot \varphi)^2 + z^2} = \frac{1}{2} \sqrt{(r \cdot \varphi^p)^2 + (z^p)^2} + \frac{1}{2} \sqrt{(r \cdot \varphi^r)^2 + (z^r)^2}. \quad (4.35)$$

The generalized formula for the velocity of grain material movement may conveniently be presented as follows:

$$V = \left(\frac{1}{2} \sqrt{(r \cdot \varphi^p)^2 + (z^p)^2} + \frac{1}{2} \sqrt{(r \cdot \varphi^r)^2 + (z^r)^2} \right)'.$$

Taking into account the decrease in velocity in the braking section of the helical spiral, we obtain:

$$V = \frac{r^2 \varphi^p(t) \frac{d}{dt} \varphi^p(t) + z^p(t) \frac{d}{dt} z^p(t)}{2 \sqrt{r^2 (\varphi^p(t))^2 + (z^p(t))^2}} - \frac{r^2 \varphi^r(t) \frac{d}{dt} \varphi^r(t) + z^r(t) \frac{d}{dt} z^r(t)}{2 \sqrt{r^2 (\varphi^r(t))^2 + (z^r(t))^2}}. \quad (4.36)$$

Assuming equality of the lengths of the accelerating and braking sections, $l_A=l_B$, similarly to (4.32)–(4.34), the number of turns in the braking section, n_B , the time of grain load passage through this section, t_B , and the time $t_{\max}$ were determined:

$$n_r = \frac{l_p}{2\pi r \sqrt{1 + tg^2 \beta}}, \quad (4.37)$$

$$t_r = \frac{-C_3 + \sqrt{C_3^2 - 2K_2^r (C_4 - 2n_r \pi r tg \beta)}}{K_2^r}. \quad (4.38)$$

$$t_{\max} = t_p + t_r. \quad (4.39)$$

Taking into account relations (4.18), (4.21), (4.22), (4.28)–(4.31), and (4.34)–(4.39), the final model of grain velocity in the helical channel was obtained in the form of a system of equations:

$$V = \begin{cases} \sqrt{2gh_0}, & \text{npu } t = 0, \\ \frac{r^2 \varphi^p(t) \frac{d}{dt} \varphi^p(t) + z^p(t) \frac{d}{dt} z^p(t)}{2\sqrt{r^2 \varphi^p(t)^2 + (z^p(t))^2}}, & \text{npu } t \in (0; t_p], \\ \frac{r^2 \varphi^p(t_p) \frac{d}{dt} \varphi^p(t_p) + z^p(t_p) \frac{d}{dt} z^p(t_p)}{2\sqrt{r^2 \varphi^p(t_p)^2 + (z^p(t_p))^2}} - \\ - \frac{r^2 \varphi^r(t-t_p) \frac{d}{dt} \varphi^r(t-t_p) + z^r(t-t_p) \frac{d}{dt} z^r(t-t_p)}{2\sqrt{r^2 (\varphi^r(t-t_p))^2 + (z^r(t-t_p))^2}}, & \text{npu } t \in (t_p; t_{max}), \\ \sqrt{2gh_0}, & \text{npu } t = t_{max}. \end{cases} \quad (4.40)$$

The initial grain velocity at the beginning of the accelerating section in the second and third equations of model (4.40) is taken into account in (4.18) by means of the initial conditions $C_1 \dots C_4$. Similar initial conditions for motion in the braking section are determined from (4.30) and depend on the maximum velocity V_{max} attained by the grain at the end of the accelerating section.

The proposed theoretical model takes into account the silo radius and height, the inclination angles of the accelerating and braking sections of the helical chute, the number of spiral turns, the initial velocity, as well as the sliding friction coefficient between the grain and the chute surface.

The presented analytical model determines the grain motion velocity at any moment of time both in the accelerating and in the braking part of the helical device with two discretely varying spiral inclination angles. Grain velocity control is achieved by adjusting these angles and by selecting the chute surface material with the corresponding friction coefficient.

4.2.6 Investigation of the Geometric Parameters of the Helical Channel and the Kinematic Parameters of Grain Motion

The increase in velocity in the upper part of the device is due to the need to prevent grain accumulation in the accelerating section and to avoid its spilling over the edges of

the open grain channel.

Such a combination ensures a significant increase in the velocity of the grain load in the first section of the POHC. The accelerating section 4 of the POHC (Fig. 2.21) should have the largest possible inclination angle α to the horizontal, whereas the braking section 5, with inclination angle β , should be somewhat smaller than angle α . The substantiation of the relationship between these angles follows from formulas (4.23) – (4.26) and (4.28).

At the same time, reducing the inclination angle from α to β when transitioning from one section of the device to another makes it possible to substantially reduce the velocity of gravitational descent. The decrease in velocity prevents the occurrence of critical impact forces of grain kernels against the wall and the concrete bottom of the silo, which in turn reduces or completely eliminates their mechanical damage.

For the optimal selection of the angles, it is necessary to take into account the coefficient of friction μ of the grain against the surface of the POHC trough. In addition, objective difficulties arise in determining the optimal relationship between the angles of the accelerating and braking sections for different grain crops. To ensure a steady flow of the grain mass along the helical surface of the device, the angle of repose of the grain, which depends on the grain crop variety, must also be taken into account.

The inclination angle of the braking section β must be greater than the grain friction angle ξ of the agricultural crop being loaded into the silo [24, 78]. This condition ensures steady movement of the grain load along the channel surface. Therefore, the choice and relationship between the inclination angles of the accelerating and braking sections of the POHC depend on formula (4.28) and on the specific grain variety with the corresponding friction angle ξ .

For the vast majority of agricultural grain varieties, the friction angle lies within the range from 15° to 25° , depending on the physical and mechanical properties and the moisture content of the grain mass. Taking this into account, when defining the angles of the key sections of the POHC, they should be greater than the specified angular range; that is, for the braking section, the following requirement should be satisfied: $\beta > \xi$. Under the least favorable conditions of grain flow movement, angle β takes a value exceeding the upper limit of the variation range of the friction angle, namely $\beta > 25^\circ > 25^\circ$. In this

case, given the interdependence (4.28) between the angles of the braking and accelerating sections of the POHC, angle α will be greater than 41° [78].

Taking into account the above conditions for setting the inclination angles of the POHC sections, a comprehensive set of theoretical calculations was performed to determine the specific features of the formation of the geometric characteristics of the helical channel and the kinematic parameters of grain flow motion.

The most important and significant results of the theoretical study of the grain flow motion process in the POHC are presented below.

The formation of the geometry of the helical channel first of all requires determining the inclination angles of both channel sections. Thus, using relationship (4.28) between these angular parameters, a response surface was constructed (Fig. 4.3), illustrating the pattern of variation of the inclination angle of the braking section as a function of the angular parameter of the accelerating section and the ratio of the initial height h_0 of grain fall into the helical channel to the channel radius r .

From the analysis of the illustrated relationship, it is established that the main factor determining the value of angle β is the ratio between the key dimensional parameter of the POHC, namely the channel radius r , and the grain fall height h_0 . Thus, as this ratio increases from 0.1 to 1, the inclination angle of the braking section, taking into account its algebraic difference from angle α , increases from zero to almost 50° [78]. Taking into consideration the limiting conditions imposed above on the values of the inclination angles of the channel sections, angle β should be formed on the basis of the h_0/r ratio being equal to 0.6–0.7 and higher. In this case, this angle will definitely exceed the limiting boundary of 25° [78].

Another indicator determining the geometric structure of the helical channel is the number of turns in an individual channel section. The calculation of the number of turns uses formulas (4.32) and (4.37) and is focused on satisfying several conditions. First, the geometric height of the accelerating and braking sections must not exceed the total height of the entire helical channel. Second, there must be a certain relationship between them in order to ensure acceptable limits for the duration of acceleration and braking of the grain flow.

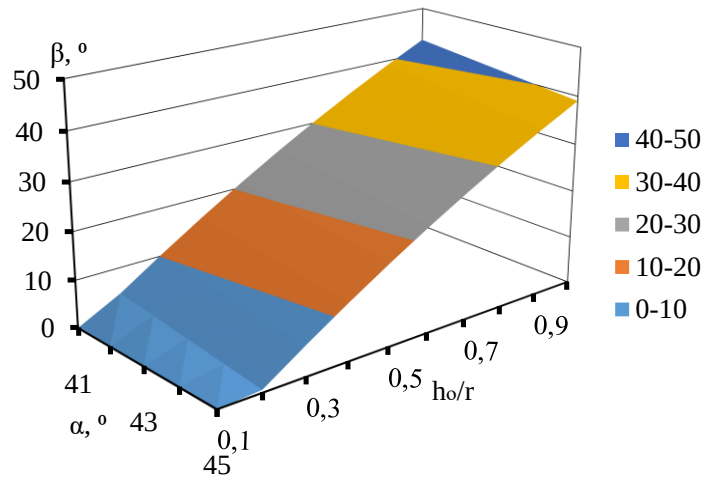
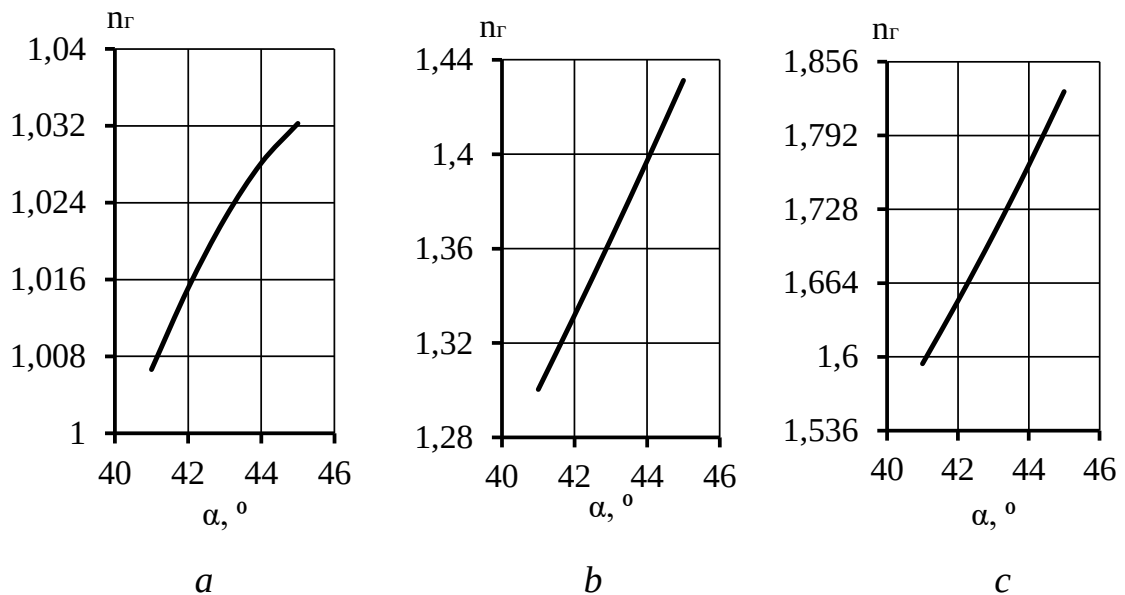


Figure 4.3 – Relationship between the angles α of the accelerating section and β of the braking section, taking into account the ratio h_0/r

Thus, Figure 4.4 shows the results of calculating the required number of turns for the braking section n_B for an arbitrarily chosen number of turns in the accelerating section n_A . The calculations were carried out for a constant ratio $h_0/r=0.7$, a helical channel height of 1.5–2.5 m, and within the range of variation of angle α from 41° to 45° [78].



$$a - n_A = 0,8; b - n_A = 1; c - n_A = 1.2$$

Figure 4.4 – Number of turns in the braking section depending on angle α and n_A at $h_0/r=0.7h$

According to the graphically presented calculation results, the number of turns n_B

tends to increase in an almost linear manner as angle α increases, regardless of the number of turns in the accelerating section. The steepest such increase in n_B with increasing angle α occurs when $n_A=1.2$, when the number of turns at the extreme points of the increasing segment differs by 14%. This is due to the rigid relationship between angles α and β , irrespective of the number of turns in the corresponding channel sections, at a constant value of the h_0/r .

4.2.7 Program for Conducting Experimental Studies of Grain Motion Velocity in the Proposed Helical Device

The purpose of the experimental studies is to determine the pattern of variation in the kinematic parameters of grain motion under the influence of governing factors and to compare them with the theoretically calculated values. This will make it possible to determine the level of agreement between the obtained results and to draw a conclusion regarding the adequacy and accuracy of the proposed analytical model and the POHC.

The maximum and final grain motion velocities were selected as the kinematic parameters to be analyzed.

In accordance with the stated objective of the experimental investigations, a research program consisting of two stages was developed.

At the first stage, the pattern of variation in the maximum grain velocity in the accelerating section was determined depending on the geometric parameters of this section. The number of factors directly influencing the formation of this criterion is quite large; therefore, in order to reduce the number of experiments, only several of them were varied. In particular, the inclination angle α of the accelerating section and the radius r of the helical channel were varied under the condition that the number of turns n_p remained constant and the grain falling height h_0 was fixed.

At the second stage, the final grain velocity at the outlet of the channel was investigated. The study was carried out by varying the inclination angles of the accelerating and braking sections while keeping the other parameters fixed, and the relationship defining the dependence between the angles was maintained.

In order to obtain reliable data, five parallel experiments were planned for each combination of variable factors at a significance level of 5%.

The obtained experimental results were processed according to the standard methodology of statistical data analysis. Specifically, this included testing the homogeneity of experimental variances using Cochran's test, checking the normal distribution of the residual series using the RS criterion, determining the relative error of the residuals and their statistical estimates, calculating the multiple correlation coefficient, and comparing the results of the experimental and theoretical studies by the magnitude of the relative errors between them. These investigations provide the basis for evaluating the accuracy and adequacy of the proposed model.

The experimental procedure involved changing the geometry of the helical channel according to the parameters selected for each stage and conducting the experiments cyclically with the required frequency and level of repeatability.

Winter wheat grain with an average moisture content of 14% was used as the grain material.

Tracking over time the movement of the grain flow along the helical channel during the experimental studies was carried out using high-speed video equipment, with selected particles marked by bright paint. Frame-by-frame analysis of the recorded material made it possible to determine the positions of key particles of the grain flow in the helical channel and to calculate the time duration of their movement. Based on the distance traveled and the duration of movement between these positions, the grain motion velocities were determined.

4.2.8 Results of Experimental Studies and Their Comparison with Theoretical Calculations

In order to verify the adequacy of the developed model of grain flow motion in the helical channel and to determine the degree of correspondence between the motion parameters obtained by calculation and their equivalent values under real conditions of gravitational grain movement, a series of experimental studies was carried out. The studies were conducted using a laboratory prototype of the peripheral open helical

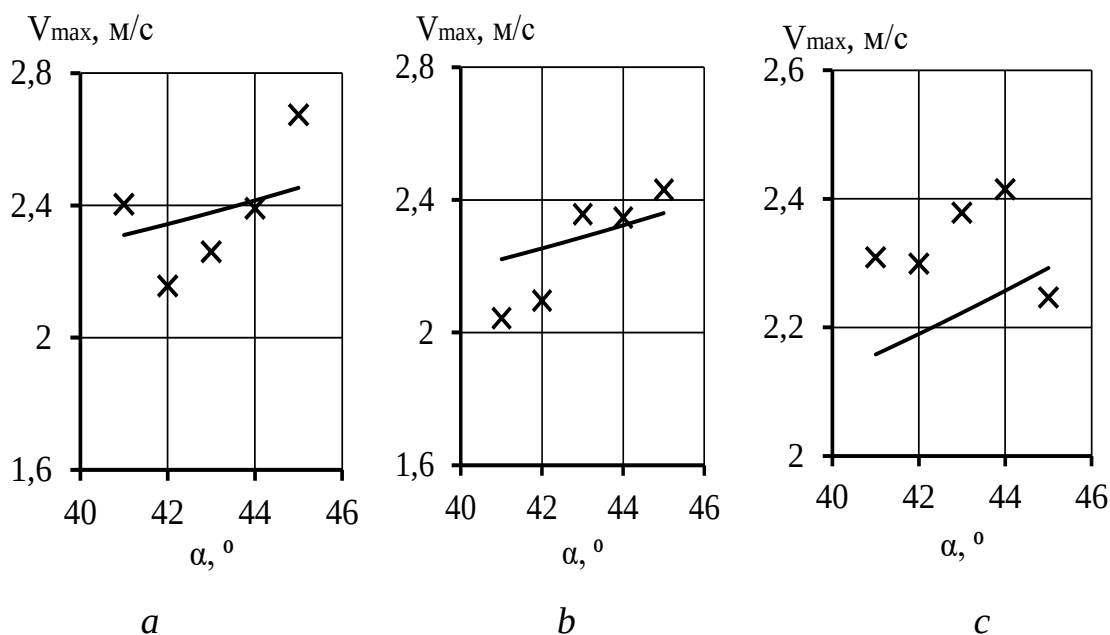
loading device (POHC) with variable descent angles (Fig. 4.5). During both the theoretical and experimental investigations, the motion of the grain flow in the helical channel was evaluated using several important kinematic parameters. These included the maximum acceleration velocity and the final grain velocity at the outlet of the helical channel.



Figure 4.5 – Experimental prototype of the POHC

With regard to the discreteness of variation of the influencing factors, the following values were adopted for the first stage of the study: the height of the helical channel was 2 m; the ratio h_0/r was selected discretely as 0.7, 0.8, and 0.9; the number of turns was $n_p=1$; the angle α varied from 41° to 45° with a step of 1° ; and the coefficient of friction of the grain material moving along the metal channel was taken as $\mu=0.3$ [78].

Figure 4.6 shows the pattern of variation in the maximum acceleration velocity within the selected range of variation of angle α . Table 4.1 presents, as an example, the results of comparing the theoretical and experimental studies for $h_0/r=0.7$.



$$a - h_0/r = 0.7; b - h_0/r = 0.8; c - h_0/r = 0.9$$

Figure 4.6 – Variation in the maximum attainable velocity of grain flow motion in the accelerating section as a function of angle α and h_0/r at $n_p=1$

According to the presented characteristics, an increase in angle α leads to an increase in the grain motion velocity, while the difference in velocity at the extreme points of the range may exceed 0.4 m/s. This is primarily caused by the increase in the inclination of the accelerating section. It should also be noted that as the ratio h_0/r increases, the rate of increase in the maximum acceleration velocity becomes more significant. Thus, for the two extreme values of this ratio, under the same angle α , the velocities differ by 0.1 to 0.4 m/s. This trend is explained by the increase in the radius r of the helical channel, which directly affects the length of the accelerating section and, accordingly, the acceleration duration.

It was experimentally established that angle α should not exceed 45° , since its further increase led to grain accumulation at the beginning of the braking section as a result of rapid gravitational sliding of the grain flow along the accelerating channel. This statement is also confirmed theoretically, since according to (4.28), when the inclination angle $\alpha > 45^\circ$, the angle $\beta < 21^\circ$, which is lower than the lower limit of the natural angle of repose ξ for wheat grain [78].

The statistical assessment of the obtained experimental data (Table 4.1) shows that

the variability of the velocity values for each angle α is rather small, and the deviations of the current values from the average do not exceed 10–13%. When checking the homogeneity of experimental variances, it was found that the observed Cochran criterion value $G=0.04525$ does not exceed its critical value $G_{\text{tab}}=0.6838$, selected according to the number of experiments, parallel tests, and accepted influencing factors. This indicates an appropriate level of quality and repeatability of the conducted experiment.

The values of the experimental error and the relative errors of the experimental and theoretical values of the maximum velocity (less than 10%) indicate entirely acceptable limits of deviation for this multifactor experiment, given the complexity of its full-scale implementation.

For the second stage of the research program, the influencing factors took the same values as in the first stage, with the ratio $h_0/r=0.9$. The angle β was calculated based on the value of angle α according to the analytical expression (4.28) presented in the theoretical part. The rule of fivefold repetition of the experiment for each angle combination was maintained at this stage as well.

To describe the process of grain flow motion along the POHC trough, taking into account the interaction of the grain with the material from which the device trough was made, the following assumptions were used:

- grain motion in the helical trough occurs as a continuous flow;
- centrifugal forces that may arise do not significantly affect the nature of the motion and can be neglected when determining the linear velocity;
- a sliding friction force arises between the supporting surface and the moving grain load, which is determined by the friction coefficient between the grain and the material from which the trough is made;
- during the movement of the grain load along the helical trough, no accumulation of grain mass occurs inside the device; otherwise, inertial motion is lost.

Table 4.1 – Results of experiments to determine the maximum motion velocity in the accelerating section ($h_0/r=0.7$)

Angle, α	Maximum velocity $V_{\max}$, m/s					Average maximum velocity $V_{\max}$	Experimental variance D_i	Theoretical maximum $V_{\max}$, m/s	Relative error, δ %
41	2,39	2,40	2,47	2,32	2,43	2,40	0,0032	2,31063	4,0
42	2,10	2,08	2,00	2,30	2,31	2,16	0,0194	2,34355	7,9
43	2,21	2,31	2,36	2,17	2,24	2,26	0,0057	2,37837	5,1
44	2,39	2,26	2,47	2,48	2,34	2,39	0,0083	2,41493	1,1
45	2,69	2,81	2,56	2,62	2,68	2,67	0,0087	2,45312	8,9
Experimental error:							0,09513		
Maximum variance, $D_{\max}$							0,01944		
Sum of variances, ΣD							0,04525		
Observed Cochran criterion value, G							0,42957		

The results of the theoretical and experimental studies aimed at determining the grain flow velocity at the outlet of the helical channel (Fig. 4.7) lead to similar conclusions. Statistical processing of the research results (Table 4.2) for determining the final velocity also indicates homogeneity of the experimental variances; in particular, the observed Cochran criterion $G=0.5446$ does not exceed its critical value of 0.6838. The values of the final velocity within one experiment do not differ significantly from their averaged values. The relative errors do not exceed 12%.

Due to the strict relationship maintained between the main geometric components of the helical channel during the experiments, it was found that the final grain outlet velocity from the channel (Fig. 4.7) lies within the range from 1.8 m/s to 2.2 m/s, with average calculated values of about 1.98 m/s.

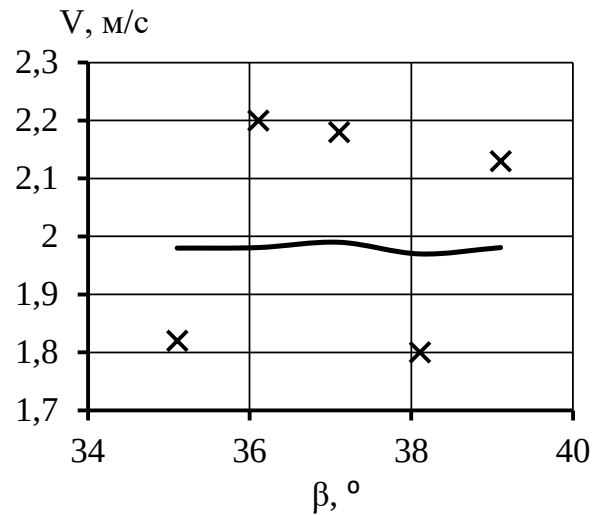


Figure 4.7 – Grain motion velocity at the moment of its discharge from the channel

Table 4.2 – Results of experiments to determine the current grain motion velocity at the moment of its discharge from the helical channel ($h_o/r = 0,9$)

Angle, α	Angle, β	Final velocity $V_{fin}, \text{m/s}$					Average final velocity $V_{fin}, \text{m/s}$	Experimental variance D_i	Theoretical final velocity $V_{fin}, \text{m/s}$	Relative error $\delta, \%$
41	39	1,98	1,9	2,6	2,3	1,9	2,14	0,0945	1,980909	7,8
42	38	1,8	1,8	1,7	1,8	1,9	1,8	0,005	1,970000	8,6
43	37	2,1	2,2	2,2	2	2,4	2,18	0,022	1,990000	9,5
44	36	2,1	2,2	2	2,4	2,3	2,2	0,025	1,980909	11,1
45	35	1,7	1,7	1,8	1,8	2,1	1,82	0,027	1,980000	8,1
Experimental error:								0,18627		
Maximum variance, D_{max}								0,09448		
Sum of variances, ΣD								0,17348		
Observed Cochran criterion value, G								0,54462		

Table 4.3 – Results of the study of residuals between experimental and theoretical data of the final grain motion velocity at the moment of discharge from the channel

Residuals V_{fin} , m/s				
-0,01	0,080909	-0,61909	-0,31909	0,080909
0,180909	0,180909	0,280909	0,180909	0,080909
-0,11	-0,21	-0,21	-0,01	-0,41
-0,11909	-0,21909	-0,01909	-0,41909	-0,319091
0,28	0,28	0,18	0,18	-0,12
Relative errors, %				
0,505051	4,258362	23,8112	13,87353	4,25836
10,05049	10,05049	16,52405	10,05049	4,25836
5,238095	9,545455	9,545455	0,5	17,0833
5,671006	9,958687	0,954556	17,46213	13,8735
16,47059	16,47059	10	10	5,71429
Average relative error, %			9,85	
Mathematical expectation:			-0,05	
Variance:			0,061	
Confidence interval:			(-0,54; 0,451)	
Sum of squared residuals:			1,52643	
RS criterion of normal distribution:			3,57 $\in$ (3,34;4,53)	

Thus, the statistical analysis of the experimental data and the residual values of the final grain outlet velocity (Tables 4.2–4.3) indicates a sufficient level and accuracy of the conducted studies. According to the RS criterion, the values of the residual series are normally distributed for a significance level of 0.05 and $n=25$. The homogeneity of the experimental variances, the multiple correlation coefficient between the experimental and theoretical data for the final velocity $R=0.998$, the average relative residual error of 9.85%, and their normal distribution all confirm the adequacy of the developed model.

The comparison of the theoretical and experimental values of the maximum and final grain motion velocities by the magnitude of the relative errors indicates an

acceptably high level of accuracy of the developed experimental POHC prototype in accordance with the investigated and substantiated analytical model.

4.3 Theoretical Modeling of the Process of Gravitational Loading of a Silo with Grain by Means of an Open Helical Channel

A reduction in grain damage during its loading into a silo can be achieved by using an open U-shaped helical channel. For this purpose, it is necessary to investigate the dynamics of grain flow motion in an open helical channel located on the inner side of the silo and having a variable pitch. This open peripheral helical channel (POHC) slows down the motion of the grain mass due to a decrease in the descent angles.

The gravitational flow of grain material along the POHC located in a cylindrical container (for example, a grain storage silo) is based on the well-known state equation of a granular medium. The state equation of a granular medium establishes the relationship between the pressure of grain particles, their shear rate, and the porosity of the grain medium [4, 21]:

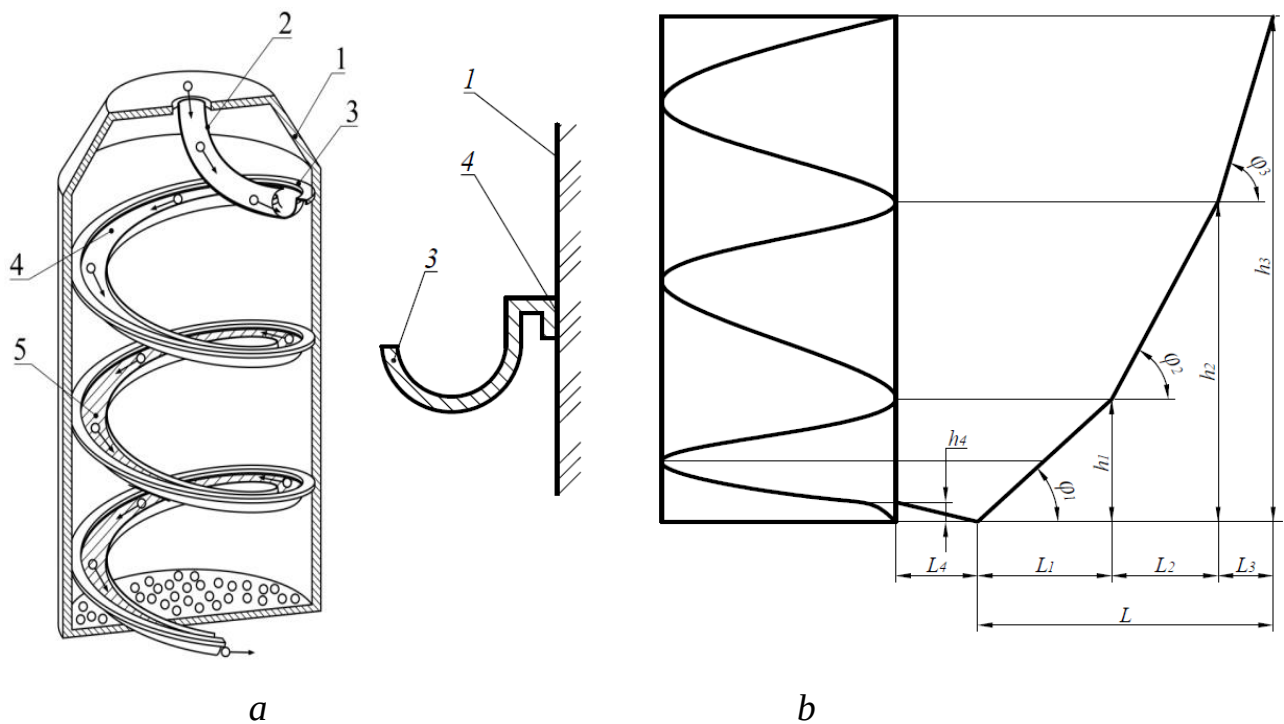
$$P(y) \cdot \varepsilon(y) = \chi \cdot \left(\frac{du}{dy} \right)^2, \quad (4.41)$$

where $P(y)$ – is the analogue of hydrostatic pressure; $\varepsilon(y)$ – is the porosity of the grain medium; χ – is a coefficient characterizing the physical and mechanical properties of the grain and the state of the entire grain medium; $\left(\frac{du}{dy} \right)^2$ – is the square of the velocity of motion of the granular grain medium.

Equation (4.41) shows that the product on its left-hand side is, in physical terms, identical to the specific work expended on the dilatation of the grain layer per 1 m³ of solid medium. The right-hand side corresponds to the kinetic energy spent on the chaotic partially structured movement of the grain medium in the POHC.

It is known that the motion of loose grain material in open chutes depends on the physical and mechanical properties of the grain, the main ones being density, roughness, brittleness, the coefficients of internal and external friction, and others.

The grain flow velocity in the open POHC is the dominant factor that significantly affects the degree of grain damage during its loading into cylindrical containers from a considerable height [122]. To reduce the velocity of wave-like and batchwise motion of grain material along the POHC, the pitch of the helical line is reduced from top to bottom.



a – helical line of a U-shaped trough with variable pitch; **b** – development of the helical line along which the trough is formed (L_1, L_2, L_3 are respectively the lengths of the helical lines with different angles ϕ_1, ϕ_2, ϕ_3); 1 – cylindrical container; 2 – throat; 3 – open helical channel; 4 – fastening; 5 – tailpiece.

Figure 4.8 – Silo with a spiral loader

Figure 4.8a presents a spiral loader for silos made along an open helical surface of a U-shaped profile with variable pitch, while Fig. 4.8b shows its development.

To formalize the process of grain flow movement along the POHC, the following assumptions were adopted: the grain moves in the form of a flow, and during motion along the working surface the grain retains its shape and mass and is not damaged. At

the same time, the motion of grain material in a U-shaped profile along a helical line with variable pitch is rather complex; therefore, the total kinetic energy of motion of an elementary layer of granular material (Fig. 4.9) can be represented as the sum of the kinetic energies of translational motion (shear), chaotic motion (fluctuation) of the grains, and circular mass transfer [21].

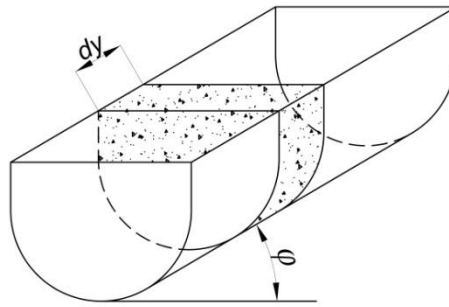


Figure 4.9 – Calculation scheme for determining the kinetic energy of an elementary layer of granular material in the trough [4]:

$$T_{cym} = T_n + T_\phi + T_m \quad (4.42)$$

where T_n – is the kinetic energy of translational motion of the granular grain layer along the POHC;

T_ϕ – is the kinetic energy of chaotic motion of grain (fluctuation) within the granular grain layer;

T_m – is the kinetic energy of circular mass transfer of granular grain material relative to the central axis of the cylindrical container.

The kinetic energy of an elementary grain layer in relative translational motion in the first section with angle φ , can be represented by the following expression:

$$T_n = \frac{1}{2} m_3 \cdot (\Delta y)^2 \cdot \left(\frac{du}{dy} \right)^2, \quad (4.43)$$

where m_3 is the mass of the elementary grain volume located in the helical channel over the length dy ;

(Δy) – is the difference in coordinates of adjacent grain layers.

The mass of an elementary grain volume located in the POHC over an infinitesimal length dy , is:

$$m_3 = S \cdot dy \cdot \rho, \quad (4.44)$$

where S – is the cross-sectional area of the helical channel (Fig. 4.10);

ρ – is the bulk density of the grain.

The cross-sectional area of the U-shaped working element is determined by the expression:

$$S = \frac{\pi r^2}{2} + 2rc = \frac{r}{2}(\pi + 4c), \quad (4.45)$$

where r and c are respectively the radius and the height of the helical channel.

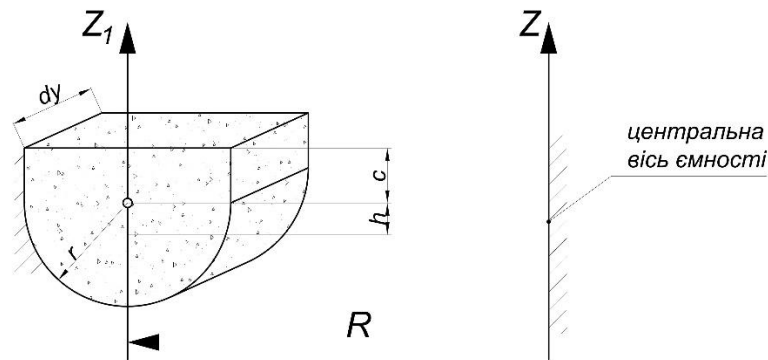


Figure 4.10 – Calculation scheme for determining the moment of inertia of the grain layer of an elementary volume relative to the central axis of the silo

Substituting (4.45) into (4.44), we obtain the mass of the elementary grain volume located in the trough of the helical channel:

$$m_3 = \frac{r}{2}(\pi + 4c)\rho \cdot dy. \quad (4.46)$$

Taking into account that the displacement of elementary grain layers of loose material in the working element occurs with a change in the coordinate difference, then:

$$\Delta y = y_1 - y_2, \quad (4.47)$$

where y_1 and y_2 are respectively the coordinates of the centers of adjacent grain layers moving downward along the POHC under the action of gravity with a variable inclination angle.

Substituting (4.46) and (4.47) into (4.43), we obtain:

$$T_n = \frac{r}{4} (\pi r + 4c) \rho \cdot (y_1 - y_2)^2 \left(\frac{du}{dy} \right)^2 \cdot dy. \quad (4.48)$$

During the gravitational movement of grain material along the POHC, which surrounds the inner side of a cylindrical container (for example, a grain storage silo), impact impulses arise between individual kernels in the grain flow. In the general case, impact impulses are the result of oblique collisions of kernels in the grain flow and, according to [4, 93], are determined by the Ackermann–Schoen method:

$$\gamma = \frac{\tau}{E \cdot z} \cdot \frac{du}{dy}, \quad (4.49)$$

where τ – is the shear stress;

E is the kinetic energy dissipated by two kernels during a single contact; n is the number of kernels in the elementary volume of a grain layer of length dy .

Knowing the average collision frequency makes it possible to determine the average fluctuation velocity of the grains. For this purpose, we use the formula given in the literature [93]:

$$\bar{u}' = \gamma \cdot b, \quad (4.50)$$

where b – is the average distance between two kernels relative to their reduced masses.

The kinetic energy associated with the chaotic movement of the grain mass in the POHC arises due to changes in the relative tangential velocities of individual kernels as a result of their oblique collisions. This kinetic energy is determined by the following expression:

$$T_{\phi} = \frac{1}{2} m_3 \cdot (\bar{u}')^2. \quad (4.51)$$

Substituting (4.46), (4.49), and (4.50) into (4.51), we obtain:

$$T_{\phi} = \frac{1}{4} r(\pi r + 4c) \rho \left(\frac{\tau \cdot du}{E \cdot z \cdot dy} \right)^2 b^2 dy. \quad (4.52)$$

Because grain storage silos have considerable overall dimensions, the installation of a helical channel on the inner surface of the silo causes the grain mass to move not only translationally, but also to perform slight rotational motion relative to the central axis of the silo. In this case, the kinetic energy of circular mass transfer [4, 21] is:

$$T_{\mathcal{M}} = \frac{1}{2} I_z \cdot \omega^2, \quad (4.53)$$

where I is the moment of inertia of the continuous grain medium of volume dV , located in the POHC and moving relative to the central axis of a silo of radius R ; ω - is the angular velocity.

The moment of inertia of the continuous grain medium of elementary volume dV and shape corresponding to the shape of the helical channel in its cross section, according to the Huygens–Steiner formula [4, 21], is:

$$I_z + I_{z_1} + m_3 R^2, \quad (4.54)$$

where I_{z_1} – is the moment of inertia of the grain layer of the elementary volume relative to the central axis of symmetry of the cross section of the helical channel (Fig.

4.10);

R is the radius of the silo container.

The moment of inertia I_{z_1} consists of the moments of inertia of the individual figures from which the peripheral helical channel is formed. Then:

$$I_{z_1} = \frac{1}{16} m_3 r + \frac{1}{2} m_3 h, \quad (4.55)$$

where $h = \frac{2r}{3\pi}$.

or

$$I_z = \frac{r^2}{32} (\pi r + 4c) \rho \cdot dy + \frac{r^3}{54\pi^2} (\pi r + 4c) \rho \cdot dy + \frac{r}{2} (\pi r + 4c) \rho \cdot R^2 dy. \quad (4.56)$$

Substituting (4.56) into (4.53), performing some transformations, and taking into account that $\omega = V/R$, we obtain:

$$T_{\mathcal{M}} = \frac{r}{4} (\pi r + 4c) \cdot \rho \cdot \left(\frac{V}{R} \right)^2 \left(\frac{r}{16} + \frac{r^2}{27\pi^2} + R \right) dy. \quad (4.57)$$

The total kinetic energy of the grain flow will be:

$$\begin{aligned} T_{\text{сум}} &= \frac{r}{4} (\pi r + 4c) \rho (y_1 - y_2)^2 \left(\frac{du}{dy} \right)^2 dy + \frac{r}{4} (\pi r + 4c) \rho \left(\frac{\pi du}{Ez dy} \right)^2 b^2 dy + \\ &+ \frac{r}{4} (\pi r + 4c) \rho \left(\frac{r}{16} + \frac{r^2}{27\pi} + R^2 \right) \cdot \left(\frac{V}{R} \right)^2 dy = \frac{r}{4} (\pi r + 4c) \rho \left(\frac{du}{dy} \right)^2 dy [(y_1 - y_2)^2 + \\ &+ \left(\frac{\pi b}{Ez} \right)^2 + \left(\frac{r}{16} + \frac{r^2}{27\pi} + R^2 \right) \cdot \left(\frac{V}{R} \right)^2 \left(\frac{dy}{du} \right)^2]. \end{aligned} \quad (4.58)$$

Formula (4.58) includes the dissipation of kinetic energy (E)(E)(E), which arises as a result of one collision between two kernels. This energy can be determined [4, 93] as follows:

$$E = \frac{1}{2} m_3 \left(\frac{1-K^2}{4} + \frac{f(1+K)}{\pi} - \frac{f(1+K)^2}{4} \right) (\bar{u}')^2, \quad (4.59)$$

where k is the coefficient of restitution during impact; f is the coefficient of friction between individual kernels; $\bar{u}'$ – is the fluctuation velocity of the grains during their movement along the helical channel.

The fluctuation velocity of grains during their movement along the POHC can be determined through the change in the relative tangential velocity acquired by the grains as a result of oblique collisions:

$$\bar{u}' = -\Delta u / f(1+K), \quad (4.60)$$

where Δv_τ is the change in the relative tangential velocity acquired by the grains as a result of oblique collisions.

The dissipation of kinetic energy, taking into account (4.46) and (4.60), is:

$$\begin{aligned} E &= \frac{\Delta u^2}{4 f^2 (1+K)^2} r(\pi r + 4c) \rho \left(\frac{1-K^2}{4} + \frac{f(1+K)}{\pi} - \frac{f(1+K)^2}{4} \right) dy = \\ &= \frac{\Delta u^2}{4} r(\pi r + 4c) \rho \left(\frac{1-K}{4 f^2 (1+K)} + \frac{1}{\pi f (1+K)} - \frac{1}{4 f} \right) dy = \\ &= \frac{\Delta u^2 r(\pi r + 4c) \rho}{16 f^2 \pi (1+K)} [\pi(1-K) + 4f - f\pi(1+K)] dy. \end{aligned} \quad (4.61)$$

After making some simplifications in formula (4.61), denoting the expressions $[\pi(1-K) + 4f - f\pi(1+K)] = g$ and substituting these simplifications $\frac{r}{2}(\pi r + 4c)dy = dv$, the formula for kinetic energy dissipation takes the following form:

$$E = \frac{\Delta u^2 dv \cdot \rho \cdot g}{8 f^2 (1+K) \pi}, \quad (4.62)$$

V is the elementary volume of the grain layer located in the open U-shaped peripheral helical channel.

The obtained relations (4.58) and (4.62) constitute a mathematical model that characterizes the total kinetic energy of movement of elementary grain volumes in the open helical channel and takes into account the physical and mechanical properties of the bulk material and the shape of the silo.

Substituting (4.58) into (4.41), we obtain the state equation of the loose grain medium moving under the action of gravitational force in the open peripheral helical channel of a cylindrical container in the following form:

$$\rho \cdot \bar{\varepsilon} = \chi \frac{r}{4} (\pi + 4c) \rho \left(\frac{du}{dy} \right)^2 \left[(y_1 - y_2)^2 + \left(\frac{\tau \cdot b}{E \cdot z} \right)^2 + \left(\frac{r}{16} + \frac{r^2}{27\pi} + R^2 \right) \left(\frac{Vdy}{Rdu} \right)^2 \right] dy. \quad (4.63)$$

where $\bar{\varepsilon}$ – is the average porosity of the grain medium.

The obtained relations (4.58), (4.62), and (4.63) can be used for the analysis and substantiation of the parameters of the open peripheral helical channel, which can be used for gentle loading of cylindrical silo-type containers with grain.

The obtained state equation of the loose grain medium moving under the action of gravitational forces in the helical channel makes it possible to investigate the motion of the grain medium in a trough having the shape of a helical line and located inside a cylindrical container. To reduce the velocity of grain flow movement, it is proposed that the helical channel should be made with a variable pitch.

If you want, I can also polish this fragment into a more monograph-style academic English version with unified terminology throughout the chapter.

4.4 Mathematical Study of Grain Motion Along a Helical Surface with Variable Screw Pitch

Let us consider two points in a plane coordinate system with coordinates $A(x_0, y_0)$ and $B(x_k, y_k)$ [74]. It is necessary to determine the profile of a helical channel with a variable descent angle along which the grain mass will move downward from point A to

point B. At the beginning of the loading process (point A), the grain material is located above the container; as a result of loading, it enters the container and occupies one or another horizontal layer located below the initial position (Fig. 4.11).

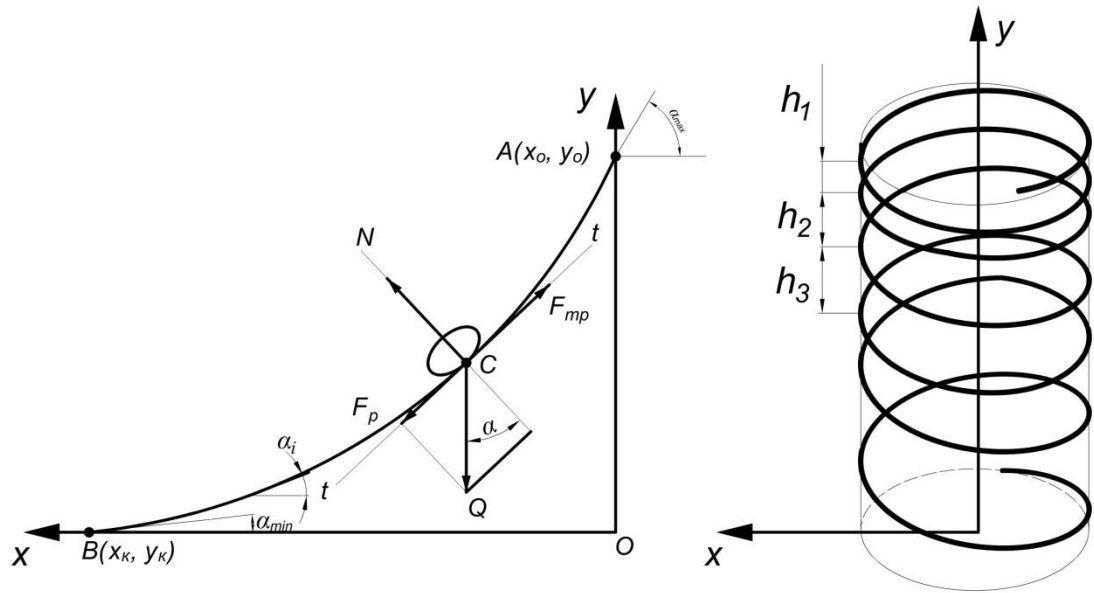


Figure 4.11 – Diagram of the forces acting on an element of the grain mass during its motion along a helical surface

Let the grain material, moving along the POHC, reach point C. At this point, three forces act on the grain mass: the weight of the selected element of grain mass Q, the normal reaction of the helical channel N, and the friction force F_T .

The equation of motion of the grain mass element in the tangential direction, обозначен? along the axis $t-t$ in Fig. 4.11, has the form:

$$m \frac{d^2 l}{dt^2} = Q \cdot \sin \alpha(l) - Q \cdot f_T \cdot \cos \alpha(l), \quad (4.64)$$

or

$$\frac{d^2 l}{dt^2} = g \cdot \sin \alpha(l) - Q \cdot f_T \cdot \cos \alpha(l)$$

Assuming that α varies according to the law $\alpha(l) = -a \cdot l + \alpha_{\min}$, where a is a constant coefficient and $\alpha_{\min}$ is the minimum descent angle.

$$\frac{d^2 l}{dt^2} = g \cdot \gamma \cdot n \cdot (-a \cdot l + \alpha_{\min}) - g \cdot f_T \cdot \cos(-a \cdot l + \alpha_{\min})$$

Separating the variables, we obtain:

$$\frac{d^2 l}{g \cdot \sin(-a \cdot l + \alpha_{\min}) - g \cdot f_T \cdot \cos(-a \cdot l + \alpha_{\min})} = dt^2, \quad (4.65)$$

or

$$\left(\int \frac{dl}{g \cdot \sin(-a \cdot l + \alpha_{\min}) - g \cdot f_T \cdot \cos(-a \cdot l + \alpha_{\min})} \right) dl = \left(\int dt \right) dt$$

After introducing the substitutions $x = -a \cdot l + \alpha_{\min}$; $dx = -a \cdot dl$, we obtain:

$$\left(-\frac{1}{ag} \int \frac{dx}{\sin x - f_T \cos x} \right) dl = (t + C) dt.$$

Considering the integral on the left-hand side and introducing the universal trigonometric substitution, we obtain:

$$\begin{aligned} & \left[\begin{aligned} tg \frac{x}{l} &= t \\ \sin x &= \frac{2 \cdot t}{1+t^2} \\ \cos x &= \frac{1-t^2}{1+t^2} \\ dx &= \frac{2 \cdot dt}{1+t^2} \end{aligned} \right. \\ & = -\frac{1}{a \cdot g} \int \frac{\frac{2}{1+t^2} dt}{\frac{2 \cdot t}{1+t^2} - f_T \cdot \frac{1-t^2}{1+t^2}} = -\frac{1}{a \cdot g} \int \frac{2t}{2 \cdot t - f_T + f_T \cdot t^2} = -\frac{2}{a \cdot f_T \cdot g} \int \frac{dt}{t^2 + \frac{2}{f_T} \cdot t - 1} = \\ & = \frac{-2}{a \cdot t \cdot g} \int \frac{dt}{\left(t^2 + \frac{2t}{f_T} + \frac{1}{f_T^2} \right) - \frac{1}{f_T^2} - 1} = -\frac{2}{af_T g} \int \frac{dt}{\left(t + \frac{1}{f_T} \right)^2 - \left(1 + \frac{1}{f_T^2} \right)}. \end{aligned}$$

Using the tabulated integral

$$\int \frac{dx}{x^2 - z^2} = \frac{1}{2z} \ln \left| \frac{x-l}{x+l} \right| + C, \text{ then where } z = \frac{\sqrt{f_T^2 + 1}}{f_T}$$

Thus, the left-hand side of the integral takes the following form:

$$\begin{aligned}
& -\frac{2}{2zf_Tg\frac{\sqrt{f_T^2+1}}{f_T}} \ln \left| \frac{t + \frac{1}{f_T} - \frac{\sqrt{f_T^2+1}}{f_T}}{t + \frac{1}{f_T} + \frac{\sqrt{f_T^2+1}}{f_T}} \right| + C = \frac{-1}{zg\sqrt{f_T^2+1}} \ln \left| \frac{f_T t - \sqrt{f_T^2+1} + 1}{f_T t + \sqrt{f_T^2+1} + 1} \right| + C = \\
& = -\frac{1}{zg\sqrt{f_T^2+1}} \ln \left| \frac{f_T tg \frac{x}{2} - \sqrt{f_T^2+1} + 1}{f_T tg \frac{x}{2} + \sqrt{f_T^2+1} + 1} \right| + C. \tag{4.66}
\end{aligned}$$

for $x = -al + \alpha_{\min}$ we have

$$-\frac{1}{zg\sqrt{f_T^2+1}} \ln \left| \frac{f_T tg \left(-\frac{al + \alpha_{\min}}{2} \right) - \sqrt{f_T^2+1} + 1}{f_T tg \left(-\frac{al - \alpha_{\min}}{2} \right) + \sqrt{f_T^2+1} + 1} \right| + C.$$

Then

$$\frac{dl}{dt} = \frac{-(t+C)}{\left| -\frac{1}{zg\sqrt{f_T^2+1}} \ln \left| \frac{f_T tg \left(-\frac{al + \alpha_{\min}}{2} \right) - \sqrt{f_T^2+1} + 1}{f_T tg \left(-\frac{al - \alpha_{\min}}{2} \right) + \sqrt{f_T^2+1} + 1} \right| \right|}$$

Or

$$\frac{dl}{dt} = \frac{zg\sqrt{f_T^2+1} (t+C)}{-\ln \left| \frac{f_T tg \left(-\frac{al + \alpha_{\min}}{2} \right) - \sqrt{f_T^2+1} + 1}{f_T tg \left(-\frac{al - \alpha_{\min}}{2} \right) + \sqrt{f_T^2+1} + 1} \right|}. \tag{4.67}$$

Simplifying expression (4.67), we obtain the final value of the velocity of the grain flow moving along the open helical channel:

$$V = \frac{dl}{dt} = \frac{zg\sqrt{f_T^2 + 1} (t + C)}{-\ln \left| 1 + \frac{2\sqrt{f_T^2 + 1}}{f_T tg \frac{\alpha}{2} + 1 + \sqrt{f_T^2 + 1}} \right|}. \quad (4.68)$$

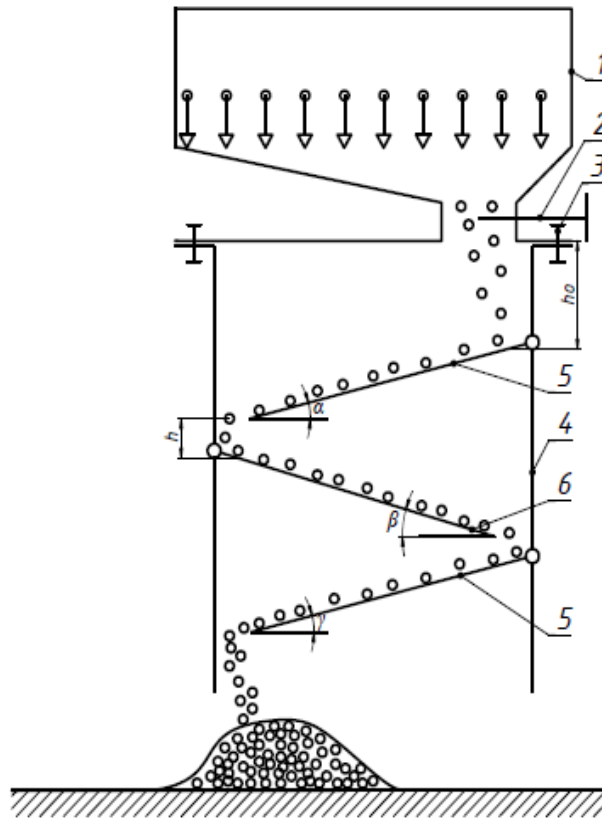
where C is an arbitrary constant determined from the condition: $t=0; V=V_0$;
 $C=V_0$.

The obtained expression shows that as the angle α decreases in the POHC, the motion of the grain flow becomes stabilized. This occurs because the pushing force of the upper layers of the grain mass decreases and, in the lower part, changes from a variable quantity to a more constant one. Therefore, in the lower part of the device, the grain material moves with an almost constant linear velocity. As a result, the grain is subjected to less damage in the lower part of the silo.

4.5 Mathematical Modeling of Grain Motion in a Gravitational-Cascade Device

4.5.1 Substantiation of the Mathematical Model of Grain Motion Along Transfer Shelves

The loading of silos, in particular tall silos, with grain kernels that differ in size, shape, and mass leads to the stratification of the grain material by density, that is, to the occurrence of segregation inside the container [24, 77, 78, 103]. This phenomenon arises during the movement of grain material along the surface of the heap and during its falling from a height. Segregation under gravitational loading also occurs during free fall from a height. The separation of grain material into fractions inside the silo considerably complicates the unloading process and may significantly deteriorate grain quality. To eliminate these negative effects, a gravitational-cascade device may be used, the description of which is given in Chapter 2.



a



b

a – schematic diagram; *b* – experimental sample

Figure 4.12 – Diagram of a gravitational-cascade device with four transfer shelves

The device consists of a hopper 1, a gate 2, a fastening unit 3, and a metal *корпус* in the form of a parallelepiped 4, inside which four transfer shelves are hinged; among them, 5 are accelerating shelves and 6 are braking shelves. The inclination angles of the transfer shelves are set by means of a special device (not shown in the figure).

Let us consider the motion of grain along the transfer shelves of a gravitational-cascade device consisting of four transfer shelves, namely two accelerating shelves of length l_1 and with inclination angles α , and two braking shelves of length l_2 and with inclination angles β and γ , respectively.

During grain motion, internal friction arises within the grain flow, as well as external friction between the shelves and the outer layer of the grain mass. We shall assume that the grain flow is discharged from the corrugated sleeve uniformly and with the same velocity, that is, we have a steady flow. It is necessary that the final grain velocity at the end of its motion along the second braking shelf be equal to the initial

flow velocity at the beginning of the first accelerating shelf, but not smaller than it. This condition will ensure gentle loading of the grain mass without damage to the kernels and will also promote grain passage without its accumulation in the sections of the braking shelves. To simplify further calculations, we shall assume that these velocities are equal to each other, $V_{\text{ноч}} \leq V_{\text{кил}}$. The distance between all four shelves is the same.

To prevent damage, the grain acquires its initial velocity V_0 as a result of falling from the hopper outlet located at a height h_0 above the edge of the first accelerating shelf. At the moment when the grain mass falls from the hopper outlet onto the initial edge of the first accelerating section, its potential energy is converted into kinetic energy, as a result of which the grain acquires the velocity V_0 . Using the law of conservation of energy, we obtain the initial grain velocity $V_0 = \sqrt{2gh_0}$.

Continuing its motion, the grain flow accelerates its velocity to V_1 , passing the distance l_1 along the first accelerating section, which is inclined at an angle α to the horizontal. This occurs as a result of the conversion of part of the grain potential energy $E_{\text{п1}} = mgl_1 \sin \alpha$ into kinetic energy. Taking into account the friction force between the grain layer and the plate surface with friction coefficient μ , which resists the acceleration of the grain mass, we obtain the simplified equation describing the energy transformation of the grain flow on the first accelerating shelf:

$$\frac{mV_0^2}{2} \sin \alpha + mgl_1 \sin \alpha - \mu mgl_1 \cos \alpha = \frac{mV_{\text{max}}^2}{2}. \quad (4.69)$$

After passing the first accelerating shelf, the grain falls from a distance h , which is the averaged value of the falling trajectories of the kernels (Fig. 4.12), onto the first braking shelf. Using the law of conservation of energy and taking into account the inclination angles of the accelerating and braking sections, we obtain:

$$\left(\frac{mV_{\text{max}}^2}{2} \sin \alpha + mgh \right) \sin \beta$$

The motion of the grain flow along the first braking shelf of length l_2 , located at an angle β to the horizontal, occurs due to the previously acquired maximum kinetic energy on the first accelerating shelf, the additional kinetic energy acquired during the fall from height h , and the grain potential energy $E_{n2} = mgl_2 \sin \beta$. At the same time, this process is opposed by the work of the friction force $A_2 = \mu mgl_2 \cos \beta$, which, due to the smaller inclination angle $\beta \leq \alpha$, is already significantly greater and causes a decrease in the grain flow velocity from $V_{\max}$ to $\frac{2V_{\max}}{3}$. Thus, after passing the first braking section, the model assumes a one-third reduction in the maximum grain velocity, which should prevent accumulation of the grain mass. From the law of conservation of energy, we have:

$$\left(\frac{mV_{\max}^2}{2} \sin \alpha + mgh \right) \sin \beta + mgl_2 \sin \beta - \mu mgl_2 \cos \beta = \frac{m \left(\frac{2V_{\max}}{3} \right)^2}{2}.$$

After passing the first braking shelf, the grain again falls from a distance h onto the second accelerating shelf. Using the law of conservation of energy and taking into account the inclination angles of the accelerating and braking sections, we obtain

$$\left(\frac{2mV_{\max}^2}{9} \sin \beta + mgh \right) \sin \alpha. \text{ Continuing its motion along the shelf, the grain flow accelerates its velocity from } \frac{2V_{\max}}{3} \text{ to velocity } V, \left(\frac{2V_{\max}}{3} \leq V \leq V_{\max} \right).$$

The motion of the grain flow along the second braking shelf, located at an angle γ to the horizontal, occurs similarly due to the previously acquired kinetic and potential energy, which is opposed by the work of the friction force, which, owing to the smaller inclination angle γ ($\gamma \leq \alpha$), is already significantly greater and causes a decrease in the grain flow velocity from V to the initial value V_0 .

4.5.2 Analytical Model of Controlled Grain Motion

By combining the above relationships that describe grain motion along the accelerating and braking sections, we obtain an analytical model of the gravitational motion of grain along the shelves of the gravitational-cascade device:

$$\left\{ \begin{array}{l} mgh_0 = \frac{mV_0^2}{2} \\ \frac{mV_0^2}{2} \sin \alpha + mgl_1 \sin \alpha - \mu mgl_1 \cos \alpha = \frac{mV_{\max}^2}{2} \\ \left(\frac{mV_{\max}^2}{2} \sin \alpha + mgh \right) \sin \beta + mgl_2 \sin \beta - \mu mgl_2 \cos \beta = \frac{2mV_{\max}^2}{9} \\ \left(\frac{2mV_{\max}^2}{9} \sin \beta + mgh \right) \sin \alpha + mgl_1 \sin \alpha - \mu mgl_1 \cos \alpha = \frac{mV^2}{2} \\ \left(\frac{mV^2}{2} \sin \alpha + mgh \right) \sin \beta + mgl_2 \sin \gamma - \mu mgl_2 \cos \gamma = \frac{mV_0^2}{2} \end{array} \right. \quad (4.70)$$

To determine the relationships that define the dependence between the inclination angles of the accelerating and braking sections, let us solve system (4.70). From the first, second, and third equations of system (4.70), we obtain the equation that defines $\angle \beta$ through a given $\angle \alpha$:

$$\begin{aligned} & \left((h_0 + l_1) \sin^2 \alpha - \mu l_1 \sin \alpha \cos \alpha + h + l_2 \right) \sin \beta - \mu l_2 \cos \beta = \\ & = \frac{4}{9} (h_0 \sin \alpha + l_1 \sin \alpha - \mu l_1 \cos \alpha) \end{aligned} \quad (4.71)$$

By equating the second, fourth, and fifth equations of system (4.70), we obtain:

$$\begin{aligned} & \left[\frac{4}{9} (h_0 + l_1) \sin^3 \alpha \sin^2 \beta - \frac{4}{9} \mu l_1 \cos \alpha \sin^2 \alpha \sin^2 \beta + (h + l_1) \sin^2 \alpha \sin \beta - \frac{1}{2} \mu l_1 \sin 2\alpha \sin \beta \right] + \\ & + l_2 \sin \gamma - \mu l_2 \cos \gamma = h_0 - h \sin \beta \end{aligned}$$

After simplifying the expression, we obtain the equation that defines γ through the angles α and β :

$$l_2 \sin \gamma - \mu l_2 \cos \gamma = h_0 - h \sin \beta - \frac{4}{9}(h_0 + l_1) \sin^3 \alpha \sin^2 \beta + \frac{4}{9} \mu l_1 \cos \alpha \sin^2 \alpha \sin^2 \beta - (h + l_1) \sin^2 \alpha \sin \beta + \frac{1}{2} \mu l_1 \sin 2\alpha \sin \beta \quad (4.72)$$

Let us solve equation (4.71). For this purpose, let us denote the first coefficient on the left-hand side and the right-hand side of equation (4.71) by a and b , respectively. We obtain trigonometric equations of the form:

$$\begin{aligned} a \sin \beta - \mu l_2 \cos \beta &= b, \\ a &= ((h_0 + l_1) \sin^2 \alpha - \mu l_1 \sin \alpha \cos \alpha + h + l_2), \\ b &= \frac{4}{9}(h_0 \sin \alpha + l_1 \sin \alpha - \mu l_1 \cos \alpha) \end{aligned}$$

Let us solve the equation by using the half-angle substitution:

$$(\mu l_2 - b) \tan^2 \frac{\beta}{2} + 2a \tan \frac{\beta}{2} - (\mu l_2 + b) = 0$$

Introducing the substitution $y = \tan \frac{\beta}{2}$ we solve the obtained equation:

$$(\mu l_2 - b)y^2 + 2ay - (\mu l_2 + b) = 0.$$

$$D = 4a^2 + 4(\mu^2 l_2^2 - b^2)$$

$$y = \frac{-a \pm \sqrt{a^2 + (\mu^2 l_2^2 - b^2)}}{\mu l_2 - b}$$

Returning to the substitution and taking into account that the angles α and β lie within the range from 0 to $\frac{\pi}{2}$, we obtain the equation describing the dependence of angle β on angle α :

$$\beta = 2 \arctg \left(\frac{-a + \sqrt{a^2 + (\mu^2 l_2^2 - b^2)}}{\mu l_2 - b} \right) + 2\pi k \quad (4.73)$$

Similarly, let us solve equation (4.72) by introducing the corresponding substitutions:

$$\begin{aligned} d &= c \sin \beta - \mu l_2 \cos \beta \\ c &= l_2 \\ d &= h_0 - h \sin \beta - \frac{4}{9}(h_0 + l_1) \sin^3 \alpha \sin^2 \beta + \frac{4}{9} \mu l_1 \cos \alpha \sin^2 \alpha \sin^2 \beta - \\ &\quad - (h + l_1) \sin^2 \alpha \sin \beta + \frac{1}{2} \mu l_1 \sin 2\alpha \sin \beta \end{aligned}$$

We obtain:

$$\gamma = 2 \arctg \left(\frac{-c + \sqrt{c^2 + (\mu^2 l_2^2 - d^2)}}{\mu l_2 - d} \right) + 2\pi k \quad (4.74)$$

Thus, we obtain a system of equations that determines the angles β and γ through a given angle α :

$$\left\{ \begin{array}{l}
a = (h_0 + l_1) \sin^2 \alpha - \mu l_1 \sin \alpha \cos \alpha + h + l_2 \\
b = \frac{4}{9} (h_0 \sin \alpha + l_1 \sin \alpha - \mu l_1 \cos \alpha) \\
\beta = 2 \arctg \left(\frac{-a + \sqrt{a^2 + (\mu^2 l_2^2 - b^2)}}{\mu l_2 - b} \right) + 2\pi k \\
c = l_2 \\
d = h_0 - h \sin \beta - \frac{4}{9} (h_0 + l_1) \sin^3 \alpha \sin^2 \beta + \frac{4}{9} \mu l_1 \cos \alpha \sin^2 \alpha \sin^2 \beta - \\
- (h + l_1) \sin^2 \alpha \sin \beta + \frac{1}{2} \mu l_1 \sin 2\alpha \sin \beta \\
\gamma = 2 \arctg \left(\frac{-c + \sqrt{c^2 + (\mu^2 l_2^2 - d^2)}}{\mu l_2 - d} \right) + 2\pi k
\end{array} \right. \quad (4.75)$$

The obtained analytical model, defined by systems of equations (4.70) and (4.75), determines the dependence of the inclination angles β and γ of the braking shelves on the inclination angle of the accelerating shelves. The model takes into account the initial height of grain fall h_0 onto the first accelerating section, the distance between the shelves h , the lengths of the accelerating and braking sections l_1 and l_2 , as well as the friction coefficient μ between the grain layer and the shelf material. The parameters selected for the study were the inclination angles β and γ of the first and second braking shelves, respectively.

4.5.3 Results of Theoretical Studies of Grain Motion Along Transfer Shelves

In the course of the experimental studies, the validity of the accepted condition of identity between the initial velocity of grain entering the gravitational-cascade device and the velocity of its discharge from the device under practical application of the theoretically substantiated geometric parameters of this device was confirmed. As a result of the experimental studies, a conclusion was drawn regarding the adequacy level of the developed analytical model.

The theoretical studies were carried out under the following conditions:

- the falling height h_{hh} of the grain from one shelf to another was assumed constant and equal to 0.2 m;
- the lengths of all shelves in the braking and accelerating sections were taken equal, $l_1=l_2=l$;
- the falling height h_0 of the grain from the hopper to the first shelf of the gravitational-cascade device was 0.3 m;
- the inclination angle of the shelf in the first braking section satisfied $\beta \leq \alpha$, while the inclination angle of the shelf in the second braking section satisfied $\gamma \leq \alpha$.

The inclination angle α of the shelves in the accelerating sections and the shelf length l were taken as variable factors. At the same time, angle α varied within the range from 40° to 75° , while the shelf length was taken in the range of 0.2 to 0.6 m.

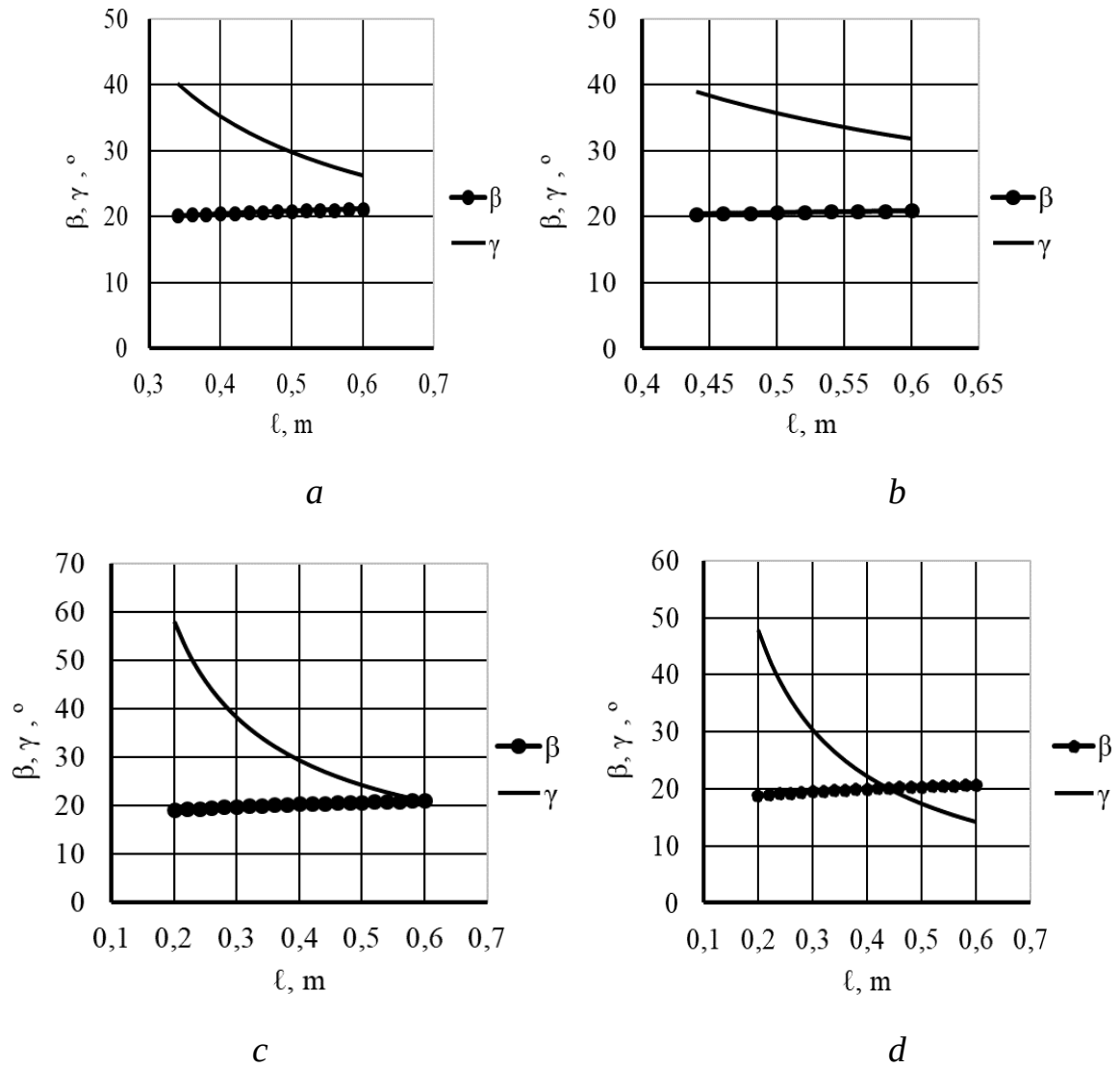
The defining parameters of the theoretical studies were the inclination angle β of the shelf in the first braking section and the inclination angle γ of the shelf in the second braking section. At the same time, only those results were analyzed in which both angles were less than or equal to the inclination angle α of the accelerating shelves. This condition is explained by the need to comply with the initial assumptions adopted in developing the analytical model.

The calculation of the defining angles β and γ was carried out in several stages, in each of which one of the variable factors was assigned a constant value while the other varied within its accepted limits.

Thus, Fig. 4.13a–d presents the results of determining the angles β and γ when the shelf length l was varied for a series of fixed values of the inclination angle α of the accelerating sections: 40° , 50° , 60° and 75° .

From the presented graphical dependences, one may note a different pattern in the formation of the angles β and γ , both in terms of the tendency of their variation with changing shelf length l and in terms of their numerical variation ranges.

The inclination angle β of the first braking section exhibits a linear increase with increasing shelf length l for each fixed angle α . In this case, the variation range of angle β is from 18.9° to 21° for all values of angle α .



$$a - \alpha = 40^\circ; b - \alpha = 50^\circ; c - \alpha = 60^\circ; d - \alpha = 75^\circ$$

Figure 4.13 – Dependence of angles β and γ on l and α

Unlike angle β , angle γ of the second braking section is characterized by a nonlinear variation, similar to a hyperbolic dependence, and decreases as l increases. It should also be noted that for certain values of angle α , angle γ is formed only over a partial range of variation of l . In particular, at $\alpha=40^\circ$, angle γ lies within the range 31.79° to 38.91° when the shelf length l varies from 0.44 m to 0.6 m. This is due to the fact that when l decreases toward its lower limit of 0.2 m, the value of angle γ becomes greater than α . This violates the specified condition for the relationship between these angles. This limitation on angle γ also slightly corrects the range of variation of angle β . Thus, its minimum value will be 20.41° instead of 18.89° .

A similar pattern of limitations for the angles β and γ is observed at $\alpha=50^\circ$: angle γ varies only within the range 26.22° to 40.29° for $l=0.34$ to 0.6 m, while the range for β is 20.18° to 21.17° .

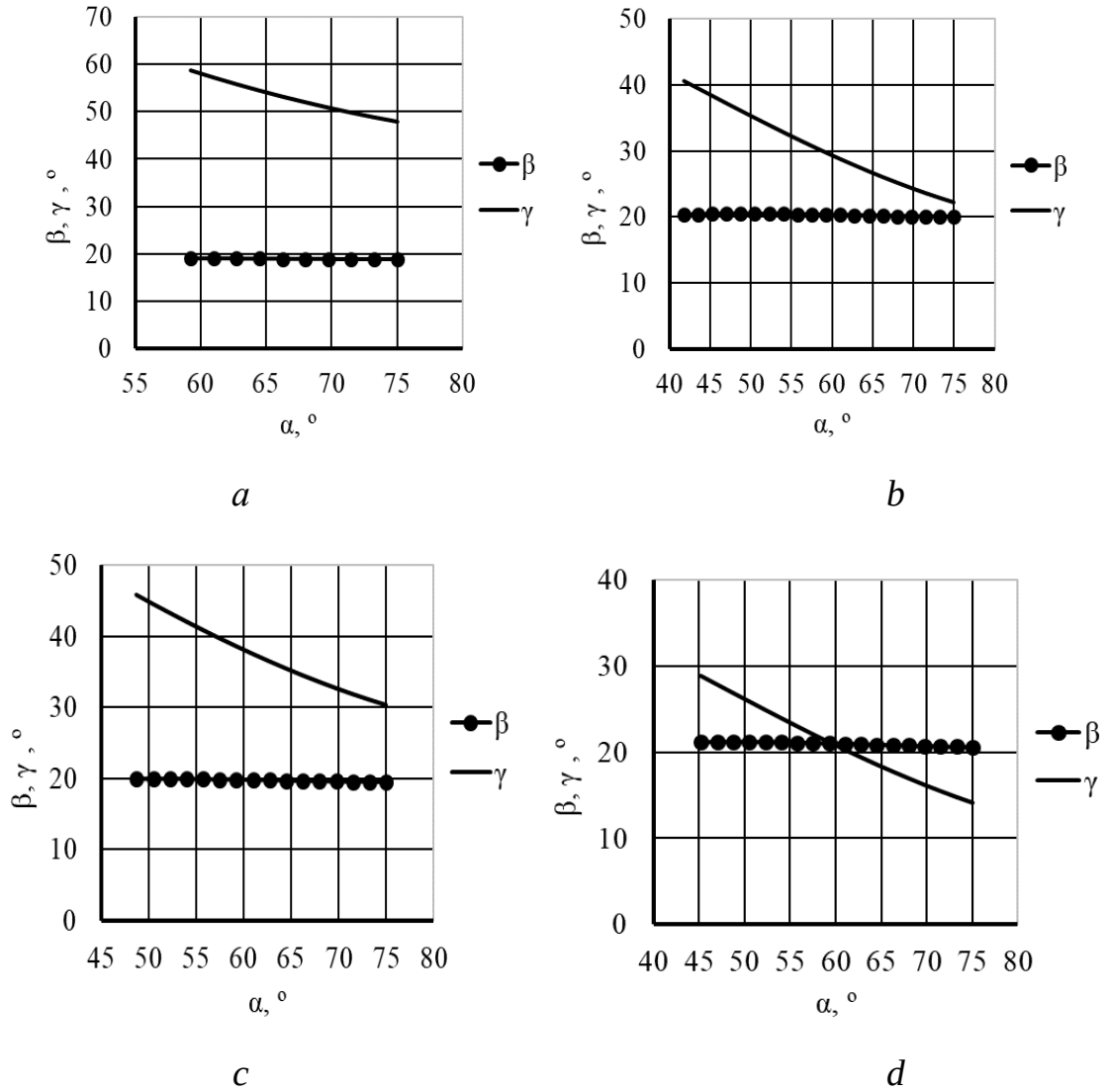
For other values of angle α , angle γ can be found over the entire accepted interval of l from 0.2 to 0.6 m. For example, at $\alpha=60^\circ$, angle γ varies from 20.84° to 58.02° , and at $\alpha=75^\circ$, $\gamma=14.18^\circ$ to 47.90° .

It should also be noted that at $\alpha=75^\circ$, the characteristics of the angles β and γ have an intersection point corresponding to an angle of 20° at a shelf length of $l=0.43$ m. This makes it possible to set the shelves of different braking sections at the same angle to the horizontal plane.

Figure 4.14 a–d presents the results of determining the angles β and γ when the inclination angle α of the accelerating sections was varied for a series of fixed shelf lengths l : 0.2 , 0.3 , 0.4 , and 0.6 m.

For both angles β and γ , an increase in angle α leads to their decrease. At the same time, the character of their variation is maximally close to linear dependences, which is most clearly observed for angle γ . In turn, the dependence of angle β on α for different shelf lengths l represents an almost flat straight-line segment, within the limits of which angle β decreases only slightly, by 0.14° to 0.32° . The absolute value of angle β , depending on the influencing factors, varies from 18.75° to 20.93° , which is significantly smaller than any accepted value of angle α and fully satisfies the condition of the relationship between these angles. In the case of angle γ , the accepted condition of its relationship with angle α is fulfilled only within a certain range of variation of α .

Thus, for $l=0.2$ m, the required relationship is achieved in the range of α variation from 59.25° to 75° , where γ decreases from 58.66° to 47.90° . As the shelf length increases, the limits of variation of the angles γ and α expand while satisfying the imposed constraints. For $l=0.3$ m, the permissible decrease in γ occurs over a wider interval of 45.83° to 30.38° as angle α increases from 48.75° to 75° . Full correspondence of angle γ to angle α over the entire range of its variation is observed only at $l=0.6$ m. In this case, γ decreases from 31.79° to 14.18° .



$$a - l = 0.2m; b - l = 0.3m; c - l = 0.4m; d - l = 0.6m$$

Figure 4.14 – Dependence of angles β and γ on α and l

It should also be noted that at $l=0.6$ m, the graphical characteristics of the angles β and γ have a common intersection point at $\alpha=60.5^\circ$, at which both angles take the same value of 21° . This makes it possible to set the shelves of both braking sections at the same angle to the horizontal plane.

Taking into account the formed and analyzed characteristics of the variation of the inclination angles of the shelves of the braking sections of the gravitational-cascade device under the influence of the governing factors, it may be stated that there is a theoretically achievable possibility of satisfying the key condition for the use of this device, namely the equality of the grain motion velocity at the inlet and at the outlet, that is, controlled grain motion.

4.5.4 Experimental Studies of Model Adequacy and Their Analysis

Based on the developed analytical model and the performed theoretical studies of the interrelationships between the angles α , β , and γ , an experimental prototype of a gravitational-cascade device with four transfer shelves was proposed. The shelves were of equal length and could freely rotate on axes fixed in the device body to the required angle inside the device relative to the horizontal plane. The angle could be set within the range from 0° to 90° . The angle value was controlled using a UN-127 vernier protractor. The horizontal plane was set by a self-leveling laser level.

For the manufacture of the shelves, sheet material cut into equal-length parts was selected. The length of each shelf was 0.4 m. The coefficient of friction of the grain material during its motion along the shelves was taken as $\mu=0.35$, based on the results of previously conducted tribological studies.

Experimental studies of grain motion along the four shelves were carried out on the proposed gravitational-cascade device for several variants of their spatial arrangement. Each shelf was positioned one below another on opposite sides of the body of the gravitational-cascade device so that, when falling from the edge of one shelf, the grain would land at the beginning of the next shelf. At the same time, the falling height of the grain from each shelf was 0.2 m. Above the device, a grain hopper was installed, the outlet neck of which was located at a distance of 0.3 m from the upper edge of the first shelf.

For the shelves of the accelerating sections, the inclination angle α was selected from the variable series 45° , 50° , and 60° . Based on angle α , according to the analytical model, the shelf of the first braking section was set at angles of 20.43° , 20.48° and 20.32° , while the shelf of the second braking section was set at angles of 38.46° , 35.28° , and 29.32° .

The grain motion velocity at the outlet of the gravitational-cascade device was tracked by recording the time of grain movement between control sections located at a distance of 0.1 m from each other. In a similar manner, the inlet velocity to the device was determined, but in this case the control distance was the height of the location of the

grain hopper outlet neck. The moment of grain appearance at a given section was determined using capacitive presence sensors.

The studies were carried out in three stages. At each stage, the angular position of the shelves was changed according to the formed variable series of inclination angles, and the inlet and outlet grain motion velocities were determined and compared. The studies were conducted with fivefold repetition for each stage

The results of the experimental studies and their statistical processing are presented in Table 4.4.

Table 4.4 – Results of experiments to determine the grain motion velocity at the inlet and outlet of the gravitational-cascade device

№	Inclination angles			Experimental results with fivefold repetition at each stage							Theoretical velocity	Absolute / relative deviation	
	α	β	γ	Average value			Maximum deviation from average		Relative deviation from average				
				V_{it}	V_{in}	Δ	V_{init}	V_{in}	V_{init}	V_{in}		V_{theor}	V_{init}
1	45	20,43	38,46	2,64	2,18	0,46	-0,21	-0,18	-8,0	-8,3	2,43	0,21 / 8,65	-0,25 / -10,31
2	50	20,48	35,28	2,54	2,62	-0,08	-0,32	-0,34	-12,6	13,0		0,11 / 4,61	0,19 / 7,99
3	60	20,32	29,32	2,74	2,30	0,44	-0,2	-0,21	-7,3	-9,1		0,32 / 13,02	-0,12 / -5,12

From the statistical analysis of the obtained experimental results, it can be seen that for each stage the initial velocity V_{init} and the final velocity V_{fin} of grain motion do not differ significantly from each other. The maximum deviation between them is 0.46 m/s, while their relative deviation from the theoretically achievable velocity $V_{theor}=2.43$ m/s does not exceed 13.02%.

In addition, it should be noted that the velocity values in each of the five experiments of a separate stage were sufficiently close. Thus, for the initial velocity V_{init}

, the maximum deviation between the velocity values was observed at the second stage and amounted to 0.32 m/s, which in relative terms equals 12.6% of the average value at this stage. For the final velocity V_{fin} , the maximum discrepancy was also observed at the second stage, when the absolute deviation amounted to 0.34 m/s with a relative equivalent of 13% of the average value. For the other stages, the discrepancies were somewhat smaller and did not exceed 0.21 m/s in absolute values and 9.1% in relative values. This indicates an appropriate level of quality and repeatability of the conducted set of experimental studies.

The values of the absolute and relative errors of the experimentally determined velocities compared with the theoretical velocity indicate entirely acceptable limits of deviation for this multifactor experiment, given the complexity of its full-scale implementation, and point to an acceptable level of accuracy of the presented analytical model.

The performed analysis indicates that the presented analytical model and the designed gravitational-cascade device, due to its braking and accelerating sections, make it possible to solve the problem of controlled grain velocity for loading into silos without damage.

The developed gravitational-cascade device makes it possible to control grain motion velocity by finding optimal angle relationships for shelves with different lengths and inclination angles. The use of gravitational-cascade devices with transfer shelves for loading grain into silos will make it possible to reduce grain damage. In addition, such devices are structurally much simpler and are not metal-intensive.

4.6 Mathematical Modeling of the Interaction of Falling Grain with a Toroidal Surface

4.6.1 General Provisions

To reduce compressive damage to grain in the lower layers of the grain heap and other undesirable effects, special devices are used, an overview of which is provided in the first chapter of this work. The considered technical means for gentle loading of containers with grain make it possible to distribute the grain load uniformly over the entire area of the container.

As such a device, which reduces the energy of grain falling from a sufficiently great height and, consequently, reduces compaction, a device for gentle loading of grain into a silo has been proposed (Fig. 4.15). The device includes a corrugated loading sleeve that can be lowered and raised inside the silo by means of a drive station located on the silo roof. In the lower part of the corrugated sleeve, a toroidal plate with outwardly curved edges is fixed. In its center there is a conical guide, whose smaller base is directed toward the inner space of the sleeve, while the bottom of the toroidal plate contains an array of through holes [77].

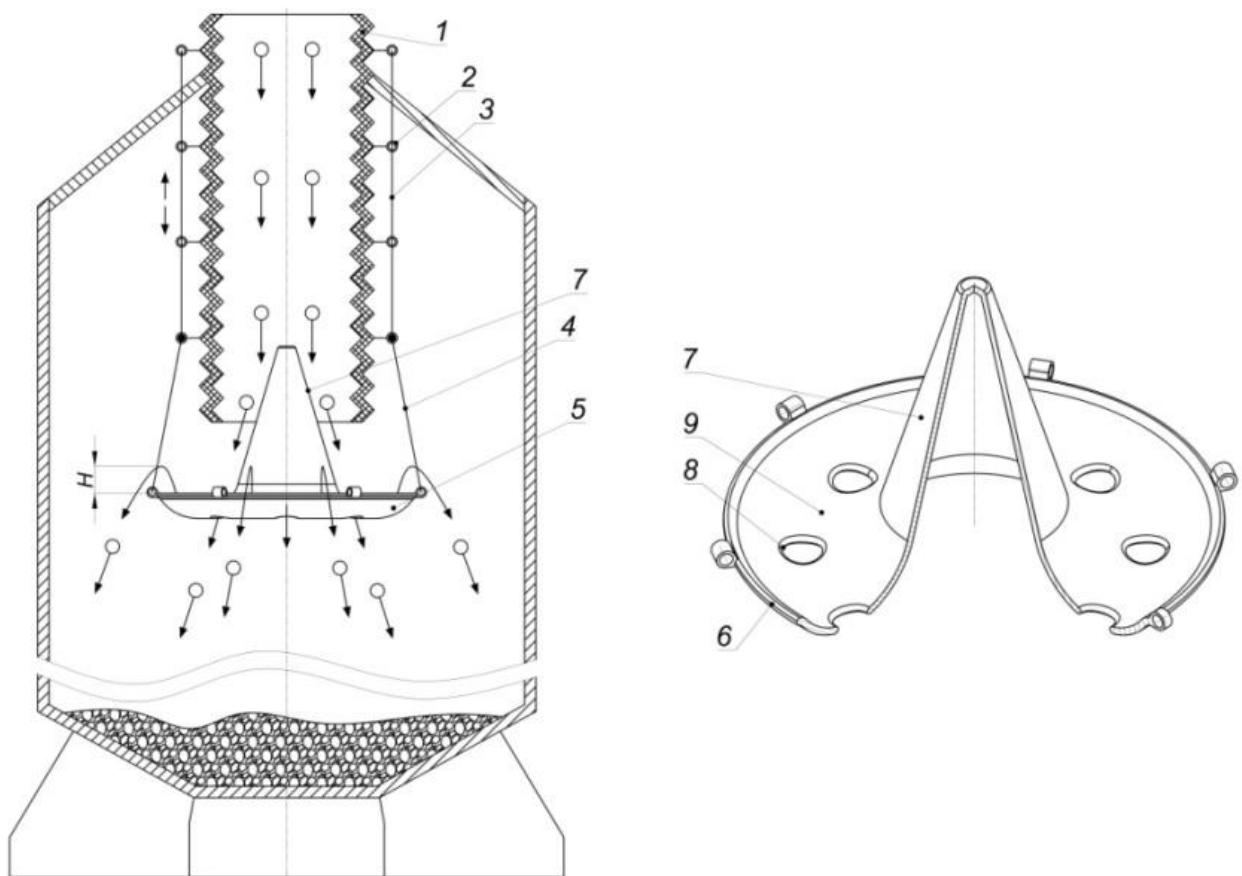


Figure 4.15 – Device for gentle loading of grain into a silo

From the loading outlet, the grain load enters the corrugated loading sleeve, which at the beginning of the loading process is located in the lower part of the silo. Under the action of gravitational force, the grain load begins to move inside the corrugated sleeve not as a continuous flow. Upon reaching the lower part, the kernels strike the conical guide of the device. As a result, the vertical motion of the grain changes direction,

directing it toward the flat bottom 9 of the toroidal plate. Under the action of a somewhat reduced gravitational force, the grain load leaves the plate along spatial curves. As a result, the grain load is distributed uniformly over the entire area of the container.

The proposed toroidal device (Fig. 4.15) consists of a corrugated sleeve 1, on the outer lateral surface of which there are guides made in the form of rings 2 with cables 3 passed through them; these cables are wound or unwound by means of a mechanical drive located at the top of the silo. By means of flexible links 4, the toroidal plate 5 is connected to the guides of sleeve 1. The toroidal plate 5 is equipped with outwardly curved edges 6, and a conical guide 7 is located in its center. A series of through holes 8 is arranged around the circumference of the plate bottom. The device for gentle loading of grain into a silo operates as follows. When it is necessary to fill an emptied silo with grain, the lifting-lowering mechanism extends the corrugated sleeve along its full length and lowers it together with the toroidal plate to the bottom of the silo. After the sleeve has been fully extended, grain mass is fed into its upper part, and under the influence of the Earth's gravitational field it moves toward the silo bottom. Upon reaching the smaller base of the central conical guide of the toroidal plate, the grain is distributed and moves in the annular gap between the guide and the inner side of the sleeve. At the same time, the width of the annular gap continuously decreases as the grain approaches the larger base of the conical guide, which makes it possible to obtain an annular grain flow with a small cross-sectional area.

Having reached the toroidal plate, the grain collides with its curved bottom surface and, due to its inertia, slides along it and is thrown upward from the plate to a certain height H , thereby dissipating excess kinetic energy, the surplus of which, in the event of collision with the silo bottom, would lead to grain damage and loss of its integrity. The curved edges of the plate improve the ejection of grain without creating excessive resistance to its motion. The part of the grain that does not have sufficient velocity to leave the plate tangentially to its inner surface falls downward through the array of holes in the plate bottom. In this case, the velocity of grain exiting the holes is considerably reduced due to multiple contact interactions of the grain both with each other in the flow and with the plate bottom surface. This also contributes to reducing the impact force of the grain against the bottom and wall of the silo itself. Under such loading conditions,

the grain load will be distributed uniformly over the entire area of the silo. Uniform distribution of grain over the entire area of the silo helps reduce pressures and segregation, which significantly decreases compressive grain damage. In this device, the annular gap between the conical guide and the inner side of the movable sleeve can be adjusted by means of flexible links.

4.6.2 Mathematical Modeling of Grain Motion Along the Working Surface of a Toroidal Device

It is known that, in addition to compressive grain damage in the lower layers of the grain heap, another undesirable phenomenon arises during gravitational loading, namely segregation. Segregation in silos occurs as a result of the nonuniform distribution of bulk material differing in size, shape, and density. Segregation of grain material is observed both at the stage of free fall of the grain and on the surface of the grain heap as a result of larger and heavier kernels rolling toward the walls of the silo container. This phenomenon leads to a reduction in the strength of the silo bin [105, 123].

The degree of segregation of grain material in silo structures is mainly influenced by the flight distance of individual kernels, which in turn depends on the physical and mechanical properties of the loaded grain. The results of the loading process, especially at the first stage, are influenced by such physical and mechanical properties of grain as bulk density, windage, flowability, moisture content, density, specific weight, and elasticity. However, the main factors affecting the uniformity of filling cylindrical containers with grain material are bulk density, windage, and grain elasticity. This is explained by the fact that when grain material falls onto the bottom of a silo structure, kernels differing in size and density acquire the same falling velocity but different values of kinetic energy, while during the stage of gravitational flight they experience different air resistance. The kinetic energy of the kernels composing the loaded material and their flight distance depend primarily on the size and mass of the particles rather than on air resistance [77]. To eliminate segregation in silos, it is necessary to use special devices that would distribute the grain load uniformly over the entire perimeter of the container.

Figure 4.16 schematically shows the operating principle of the toroidal device. Subsequently, it is necessary to determine the coordinates of grain falling onto the silo bottom. The motion of the grain before it falls onto the silo bottom can be divided into three independent sections. The first section corresponds to the free fall of the grain from the loading outlet until it comes into contact with the conical surface.

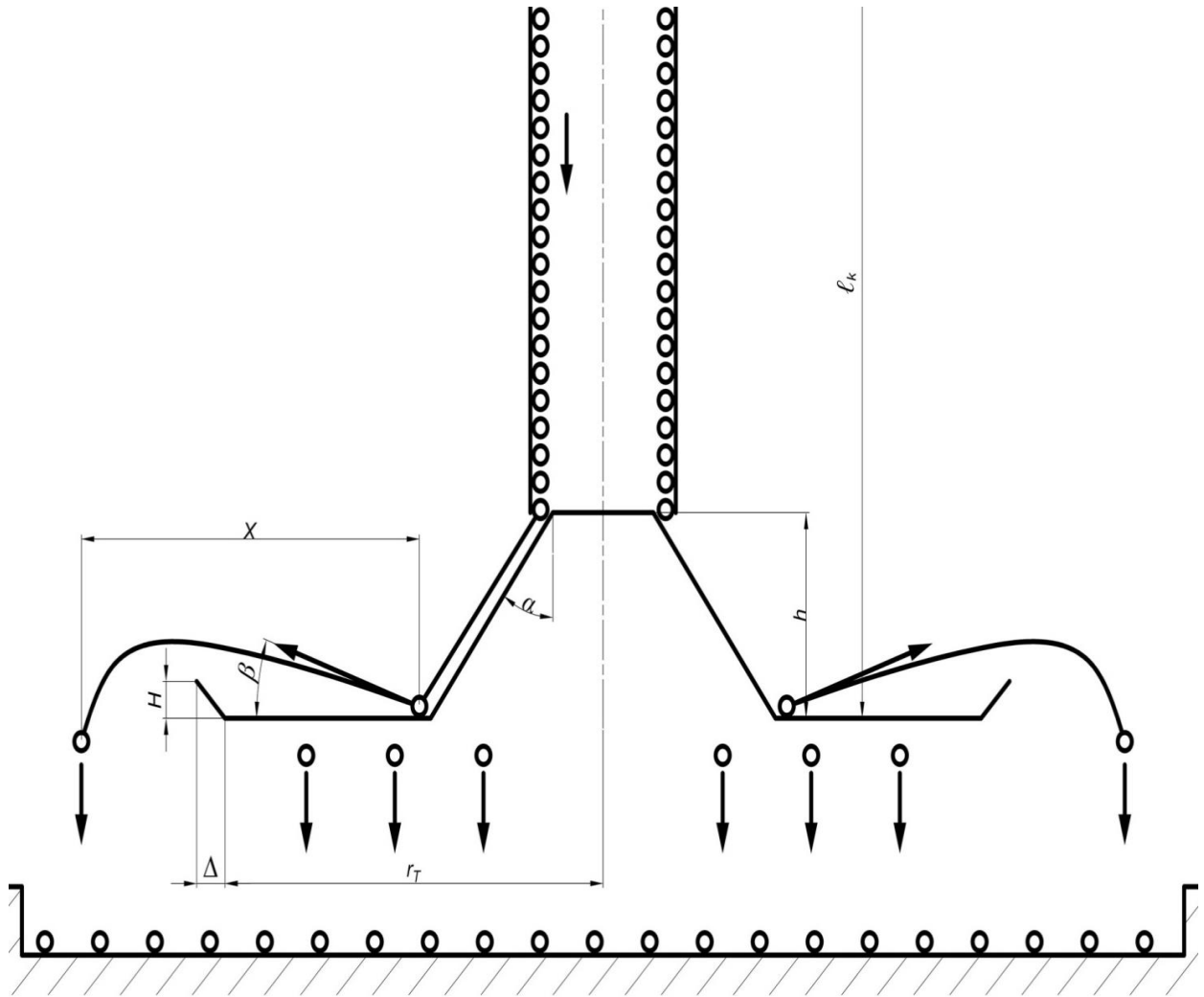


Figure 4.16 – Diagram of grain load motion in a device for gentle loading of a silo with grain

Figure 4.17 shows the motion of grain inside the corrugated sleeve (the first section) from point AAA to point BBB, that is, the free fall of grain material inside the sleeve.

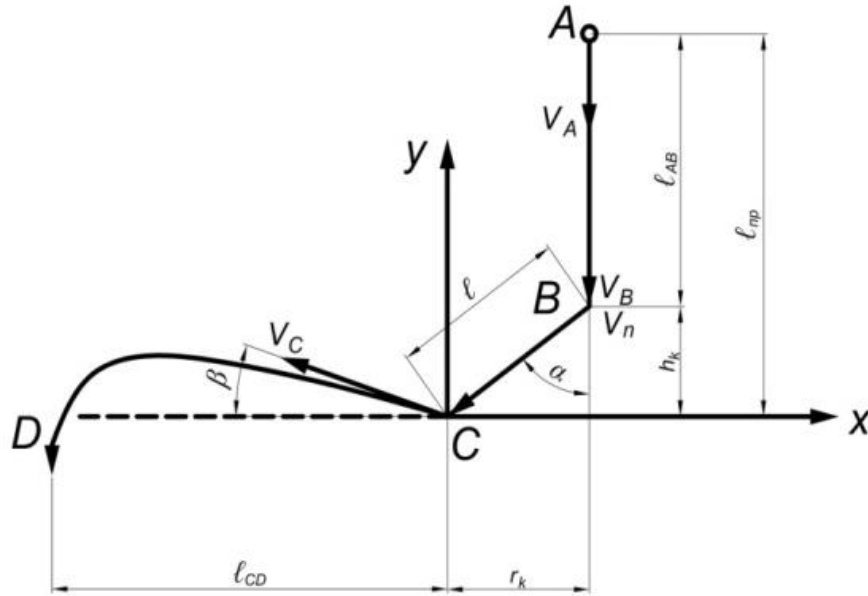


Figure 4.17 – Diagram of changes in the directions of grain load motion in a device for gentle loading of a silo with grain

Starting from point A, the grain load falls freely with the initial velocity v_A . While passing the distance AB, the grain load moves not as a continuous flow but as an aggregate of separate grain particles. The falling velocity of individual kernels increases at the moment they collide with the conical surface, and at point B it becomes equal to v_B . The path ℓ_{AB} traversed by individual kernels inside the corrugated sleeve in uniformly accelerated motion before collision with the surface of the guide cone is [121]:

$$\ell_{AB} = v_A \cdot t + \frac{g \cdot t^2}{2}. \quad (4.76)$$

The time during which a kernel passes the distance ℓ_{AB} is equal to:

$$t = \left(-v_A + \sqrt{v_A^2 + 2 \cdot g \cdot \ell_{AB}} \right) \cdot g^{-1}. \quad (4.77)$$

Substituting (4.77) into the velocity equation for uniformly accelerated motion, we obtain the grain velocity at point B, which corresponds to the apex of the toroidal plate:

$$v_B = \sqrt{V_A^2 + 2 \cdot g \cdot \ell_{AB}} . \quad (4.78)$$

The collision of the grain flow with the lateral surface of the cone is inelastic; therefore, the velocity at point B changes both in magnitude and in direction. It becomes a sliding velocity, and then the initial velocity at the apex of the cone of the device is determined by the formula:

$$v_n = v_B \cdot \cos \alpha = \sqrt{V_A^2 + 2 \cdot g \cdot \ell_{AB}} \cdot \cos \alpha . \quad (4.79)$$

In section BC, after passing through the annular gap between the corrugated sleeve and the lateral surface of the cone, the grain load forms a relatively structured, small-thickness grain flow. Upon reaching the lateral surface of the cone, individual kernels begin to perform a galloping motion, that is, they strike one another and come into contact with the grain layer. Owing to the multitude of simultaneous collisions of grain particles, the motion of these particles along the lateral surface of the cone is damped.

Using the theorem on the change in kinetic energy, the grain load velocity at point C of the toroidal plate was determined:

$$\frac{q}{2} \cdot (V_c^2 - V_n^2) = A_p - A_0, \quad (4.80)$$

where q is the feed rate of grain material onto the lateral surface of the cone; A_p is the work of the driving forces, that is, the work of gravity; A_0 is the work of friction forces.

$$\begin{cases} A_p = q \cdot g \cdot h_k \\ A_0 = q \cdot g \cdot l_{BC} \cdot f_T \cdot \sin \alpha \end{cases}$$

where h_k is the height of the cone;

g is the gravitational acceleration;

l_{BC} is the length of the cone generatrix;

α is the cone apex angle;

f_T is the coefficient of friction of the grain load against the cone surface.

Substituting A_g and A_f into formula (4.80), we obtain:

$$\frac{q}{2} \cdot (V_c^2 - V_n^2) = q \cdot g \cdot h_k - q \cdot g \cdot l_{BC} \cdot f_T \cdot \sin \alpha, \quad (4.81)$$

or

$$V_C^2 = 0,5 \cdot V_n^2 + g \cdot h_k - g \cdot l_{BC} \cdot f_T \cdot \sin \alpha. \quad (4.82)$$

We multiply and divide the third term on the right-hand side of the equation by l , and taking into account that $l_{BC} \cdot \cos \alpha = h_k$, we obtain:

$$V_C = \sqrt{0,5 \cdot V_n^2 + g \cdot h_k - g \cdot h_k \cdot f_T \cdot \tg \alpha}. \quad (4.83)$$

Substituting (4.79) into (4.83), we obtain the final velocity at point C:

$$V_C = \sqrt{0,5 \cdot V_A^2 \cdot \cos^2 \alpha + g \cdot l_{AB} \cdot \cos^2 \alpha - g \cdot h_k \cdot f_T \cdot \tg \alpha}. \quad (4.84)$$

Taking into account that $l_{AB} = l_{np} - h_k$ formula (4.84) in its final form becomes:

$$V_C = \sqrt{0,5 \cdot V_A^2 \cdot \cos^2 \alpha + g \cdot (l_{np} - h_k) \cdot \cos^2 \alpha - g \cdot h_k \cdot f_T \cdot \tg \alpha}. \quad (4.85)$$

where l_{np} – is the length of the corrugated sleeve connected to the toroidal plate.

In section CD, the grain flow, striking the bottom of the plate, is transformed into the chaotic motion of individual particles thrown at an angle β to the horizontal. After impact, the grain moves along a spatial curve. During the flight, the weight force GGG acts on it. Heavier kernels are thrown out of the plate, whereas lighter ones fall onto the plate bottom and pass through its holes to the bottom of the container.

In section CD, the grain material leaves the toroidal plate at an angle β and falls onto the silo bottom. By setting up the differential equations of motion of a kernel in a plane coordinate system in this section (air resistance forces were neglected), the flight time t and the coordinates of grain impact on the silo bottom were determined:

$$m\ddot{x} = 0; m\ddot{y} = -\sigma \quad (4.86)$$

After transformations and integration, we obtain:

$$\begin{aligned} \ddot{x} &= 0; \dot{x} = C_1; x = C_1 \cdot t + C_2 \\ \ddot{y} &= -q; \dot{y} = -q \cdot t + C_3; y = -\frac{q \cdot t^2}{2} + C_3 \cdot t + C_4. \end{aligned} \quad (4.87)$$

Let us determine the integration constants:

$$\begin{aligned} t = 0; x = y = 0; C_2 = C_4 = 0; \\ t = 0; \dot{x} = v_c \cdot \cos \beta; C_1 = v_c \cdot \cos \alpha; \\ t = 0; \dot{y} = v_c \cdot \sin \beta; C_3 = v_c \cdot \sin \alpha. \end{aligned}$$

Substituting the initial velocity and the integration constants into the equation of motion, we obtain:

$$\begin{cases} x = t \cdot \sqrt{0,5 \cdot V_A^2 \cdot \cos^2 \alpha + g \cdot (l_{np} - h_k) \cdot \cos^2 \alpha - g \cdot h_k \cdot f_T \cdot \tan \alpha \cdot \cos \beta} \\ y = -\frac{g \cdot t^2}{2} + t \cdot \sqrt{0,5 \cdot V_A^2 \cdot \cos^2 \alpha + g \cdot (l_{np} - h_k) \cdot \cos^2 \alpha - g \cdot h_k \cdot f_T \cdot \tan \alpha \cdot \cos \beta} \end{cases} \quad (4.88)$$

Let us determine the time of grain falling onto the bottom of the container. When the kernel reaches the bottom, the coordinates satisfy $y = 0$.

$$t = \frac{2 \cdot \cos \beta \cdot \sqrt{0,5 \cdot V_A^2 \cdot \cos^2 \alpha + g \cdot (l_{np} - h_k) \cdot \cos^2 \alpha - g \cdot h_k \cdot f_T \cdot \tan \alpha \cdot \cos \beta}}{g}. \quad (4.89)$$

Substituting (4.89) into (4.88), we obtain the coordinate of point D:

$$x = l_{CD} = \frac{2 \cdot (0,5 \cdot V_A^2 \cdot \cos^2 \alpha + g \cdot (l_{np} - h_k) \cdot \cos^2 \alpha - g \cdot h_k \cdot f_T \cdot \tan \alpha) \cdot \cos \beta}{g}. \quad (4.90)$$

The obtained formula indicates that by means of the toroidal plate it is possible to distribute the grain load uniformly over the entire perimeter of the silo.

4.6.3 Laboratory Setup for Investigating the Uniform Distribution of Falling Grain in a Cylindrical Container

The negative consequences of nonuniform distribution of grain material over the entire area of a container manifest themselves both during the loading and unloading of silo bins. In addition, the stratification of grain material inside a cylindrical bin leads to the formation of arches, which significantly affect the unloading of grain from the container. Increased heterogeneity of bulk grain material as a result of segregation reduces the technological suitability and consumer value of the grain [77, 124].

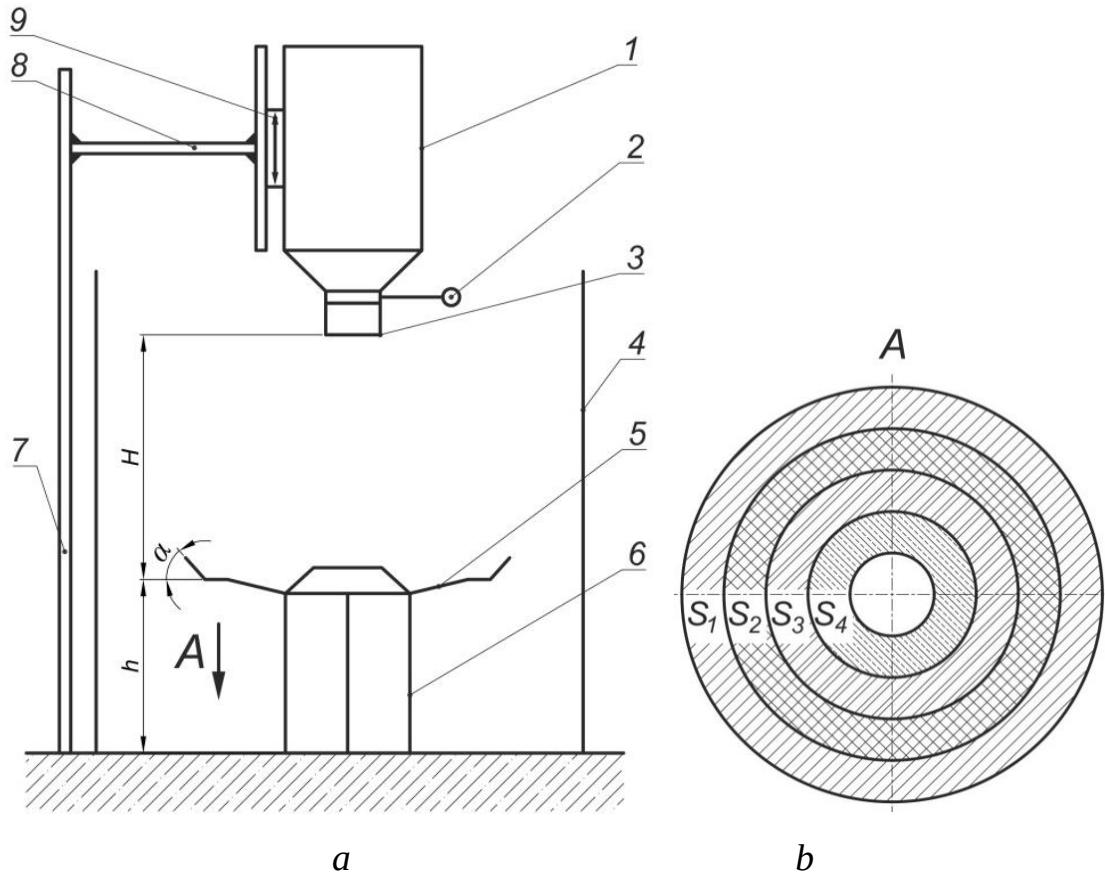
During free fall inside a silo structure, the grain material is separated into dust and grain fractions. The dust fraction becomes a source of air contamination, which is a harmful phenomenon for the health of people working at grain elevator facilities.

To investigate the character of the distribution of grain material falling from a given height onto the flat bottom of a cylindrical container, a laboratory setup was developed, which is shown in Fig. 4.18.

Winter wheat grain was used as the test grain material.

The laboratory setup (Fig. 4.18a) consists of a hopper 1, a gate 2, an outlet pipe 3, a cylindrical container 4, a toroidal plate 5, a support platform 6, a vertical post 7, a square tube 8, and a hopper lifting and lowering mechanism 9. The cylindrical container 4 simulates, to scale, a grain storage silo with a height of 24 m and a diameter of 16 m. The laboratory setup has a height of 1.2 m and a diameter of 0.8 m. Four concentric circles (Fig. 4.18b) with diameters of 0.7 m, 0.6 m, 0.5 m, and 0.4 m, respectively, were marked on the concrete bottom of the cylindrical container with colored chalk. These circles formed four annular regions S_1 , S_2 , S_3 , and S_4 . The edge of the toroidal plate,

which has a diameter of 0.16 m, is curved at an angle α to the horizontal. Three different plates with the angles $\alpha=18^{\circ}24'$, $\alpha=15^{\circ}23'$, and $\alpha=12^{\circ}51''$ were used in the experiments. The toroidal plate is installed at the center of the concrete bottom of the setup on support platform 5. The height h from the concrete bottom to the toroidal plate is constant and equal to 300 mm. A utility model patent, No. UA 15628 U [124], was obtained for the device for gentle loading of grain into a silo.



a – experimental setup; ***b*** – annular regions on the concrete bottom of the setup

Figure 4.18 – Laboratory setup

The laboratory setup operates as follows. A pre-weighed quantity of grain material is loaded into hopper 1 using electronic scales. By means of the lifting and lowering mechanism, the height H is set, from which the grain material falls under the action of gravity onto the toroidal plate and from it onto the concrete bottom of the container. When falling onto the toroidal plate, the grain comes into contact with its curved surface and, due to its inertia, slides along it and is thrown upward from the plate, thereby dissipating excess kinetic energy. Depending on the obtained velocity and the mass of

the kernels, the grain material is distributed over the circular surface of the concrete bottom of the laboratory setup. Kernels having the lowest velocity fall onto the circular surface closer to the center, while kernels with higher velocity fall farther from the center of the container. After completion of the experiments, at the set height H , the grain content from the four circular surfaces was collected into separate cups. The grain content in the cups was then weighed sequentially, and the density distribution function of the grain material was determined.

The number of repetitions required for the experiments at a selected angle α and height H was determined by the formula [125, 126]:

$$n = \frac{t^2 \cdot G^2}{(\Delta_{\text{влд}} \cdot \bar{x})^2}, \quad (4.91)$$

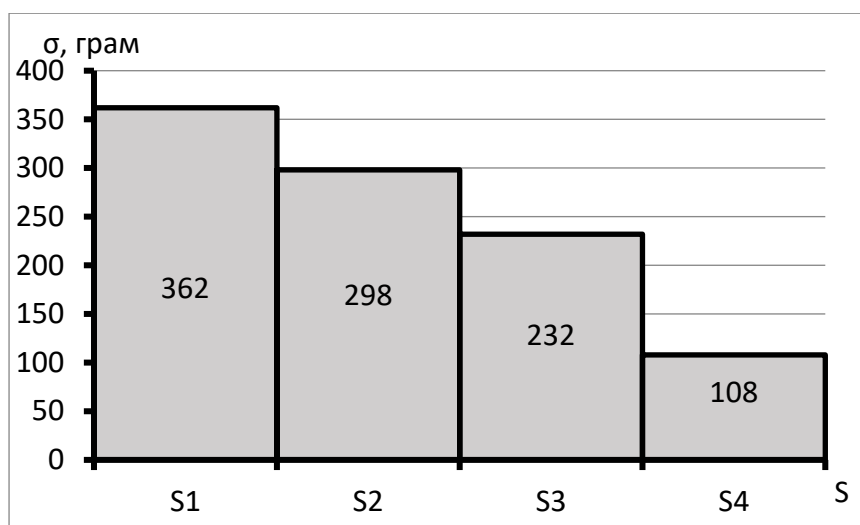
where t is Student's t -criterion; G^2 is the variance of the general population of the grain outflow time from the hopper; Δ_{rel} is the specified relative error; and $\bar{x}$ is the arithmetic mean value of the outflow time of the bulk grain material based on the results of preliminary experiments.

4.6.4 Results of Experimental Studies

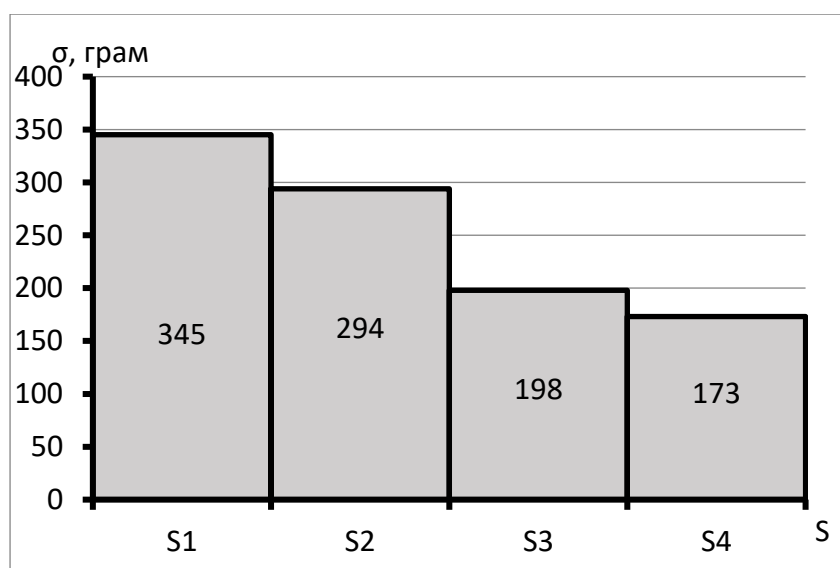
Three toroidal plates with their vertices directed downward were used in the experiments. Figures 4.19 and 4.20 present histograms showing the pattern of distribution of grain material over the bottom of the laboratory setup when using damping toroidal plates having three different inclination angles of the generatrix to the horizontal. Grain was discharged onto these plates from two heights, 1.0 m and 1.4 m, respectively.

During the interaction of the falling grain material with the working surface of the toroidal plate, the linear velocity of the grain changes both in magnitude and in direction as it falls onto the concrete bottom of the laboratory setup.

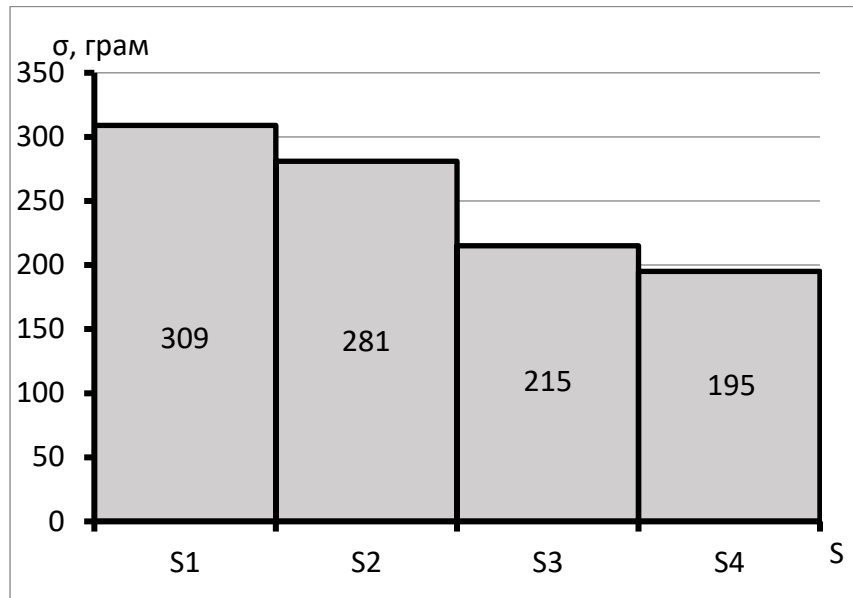
Figures 4.19 a, b, and c show histograms of the distribution of grain material over the bottom of the container depending on the three inclination angles of the plate generatrix to the horizontal. The grain material was discharged from a height of 1.0 m.



a) $\alpha=18^\circ$; $H = 1.0$ m



b) $\alpha=15^\circ$; $H = 1.0$ m



c) $\alpha=12^\circ$; $H = 1,0 \text{ m}$

a – inclination angle of the generatrix to the horizontal 18° ;

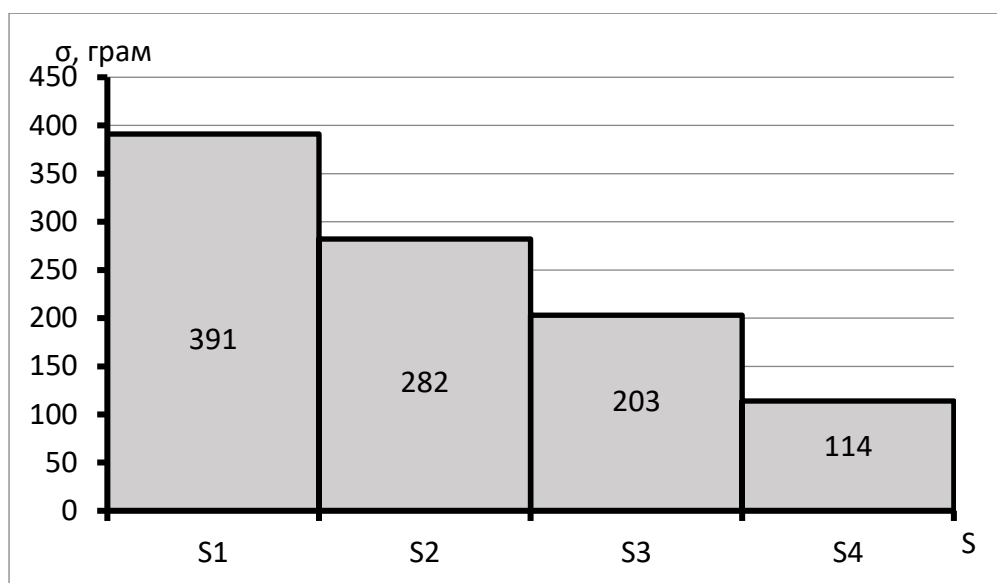
b – inclination angle of the generatrix to the horizontal 15° ;

c – inclination angle of the generatrix to the horizontal 12° .

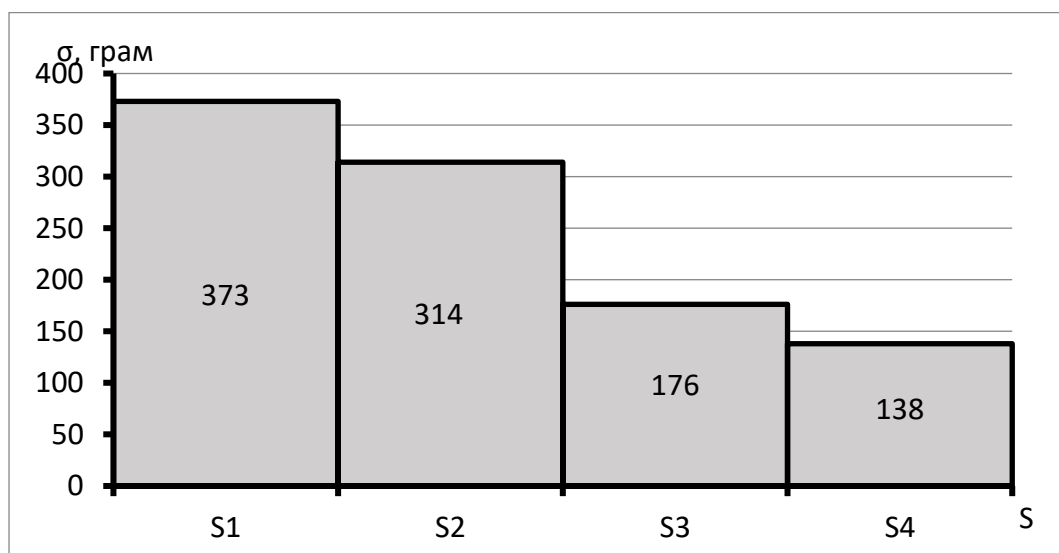
Figure 4.19 – Histograms of grain material distribution over the bottom of a cylindrical container when discharged from a height of 1 m

It can be seen from the figure that the inclination angle of the generatrix significantly affects the character of grain material distribution over the bottom of the container. At the angle $\alpha=12^\circ$, the most uniform distribution of grain material over the entire area of the container is observed.

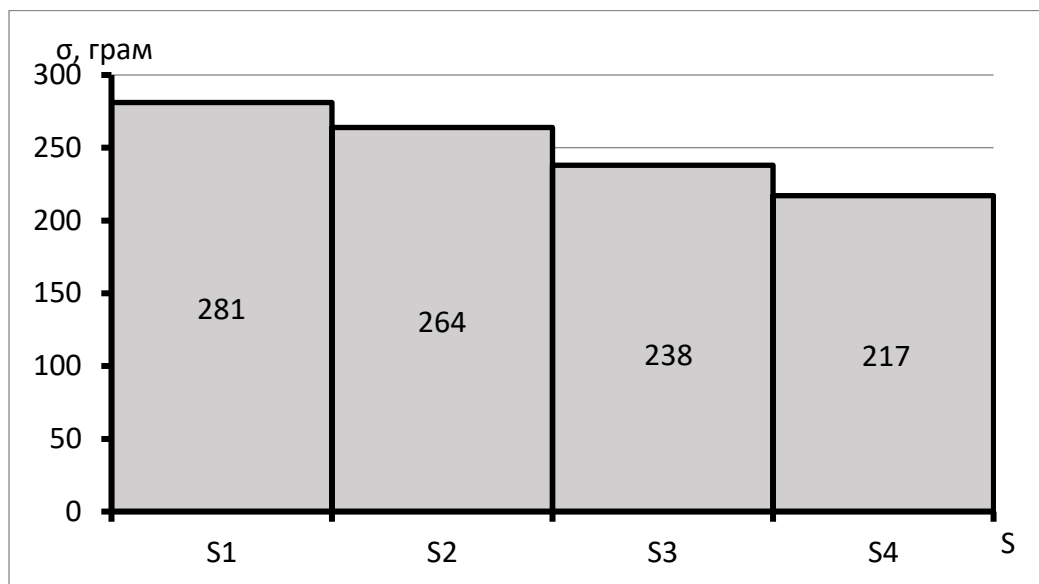
Figures 4.20 a, b, and c show histograms of grain material distribution when it is discharged from a height of 1.4 m. When falling from this height onto plates with three different inclination angles of the plate generatrix to the horizontal, it was established that the best distribution of grain material over the entire area of the container occurs at the angle $\alpha=12^\circ$. In addition, it was found that as the angle α increases, segregation of the grain material in the investigated container also increases.



a) $\alpha=18^\circ$; $H = 1,4$ m



b) $\alpha = 15^\circ$; $H = 1,4$ m



c) $\alpha = 12^\circ$; $H = 1,4$ m

a – inclination angle of the generatrix to the horizontal 18° ;

b – inclination angle of the generatrix to the horizontal 15° ;

c – inclination angle of the generatrix to the horizontal 12° .

Figure 4.20 – Histograms of grain material distribution over the bottom of a cylindrical container when discharged from a height of 1.4 m

The results of the distribution of grain material over the bottom of the laboratory setup are shown in Figures 4.21–4.23.

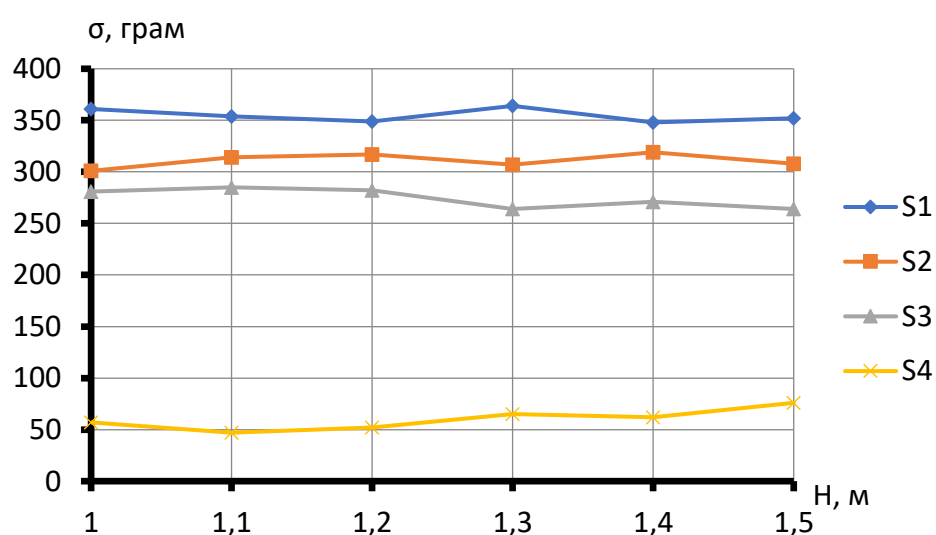


Figure 4.21 – Dependence of the distribution of winter wheat grain falling from different heights over the bottom of a cylindrical container for a toroidal plate with a generatrix inclination angle of 18° to the horizontal

It can be seen from the figure that the falling grain material is distributed differently over the circular areas. Thus, when grain was discharged from a height of 1.5 m, 324 g of grain was found in S_1 , 264 g in S_2 , 217 g in S_3 and 195 g in S_4 , respectively. Approximately the same trend in the distribution of wheat grain is observed for other discharge heights as well.

Figure 4.22 presents graphs of the distribution of winter wheat grain discharged onto the bottom of a cylindrical container using a toroidal plate with a generatrix inclination angle of 15° to the horizontal.

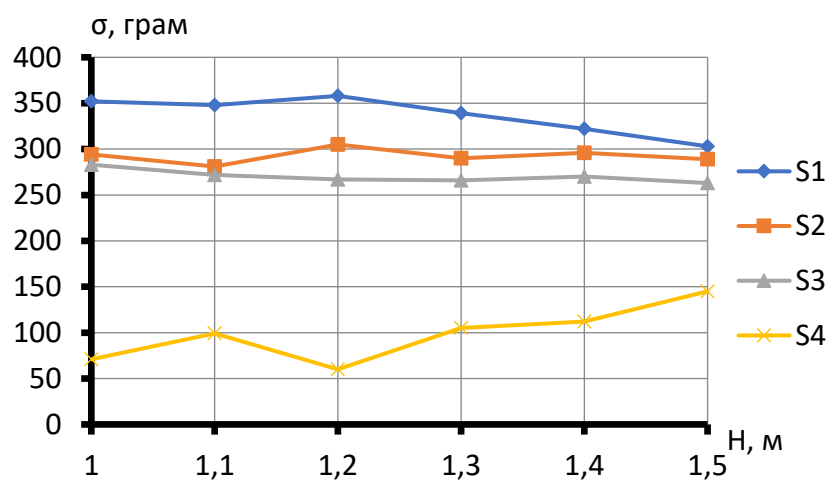


Figure 4.22 – Dependence of the distribution of winter wheat grain falling from different heights over the bottom of a cylindrical container for a toroidal plate with a generatrix inclination angle of 15° to the horizontal

It can be seen from Fig. 4.22 that when wheat grain is discharged from a height of 1.5 m, the distribution density differs somewhat from that observed in the previous experiment. Thus, 303 g of grain was found in S_1 , 289 g in S_2 , 263 g in S_3 , and 145 g in S_4 .

Figure 4.23 presents graphs of the distribution of winter wheat grain discharged onto the bottom of a cylindrical container using a toroidal plate with a generatrix inclination angle of 12° to the horizontal.

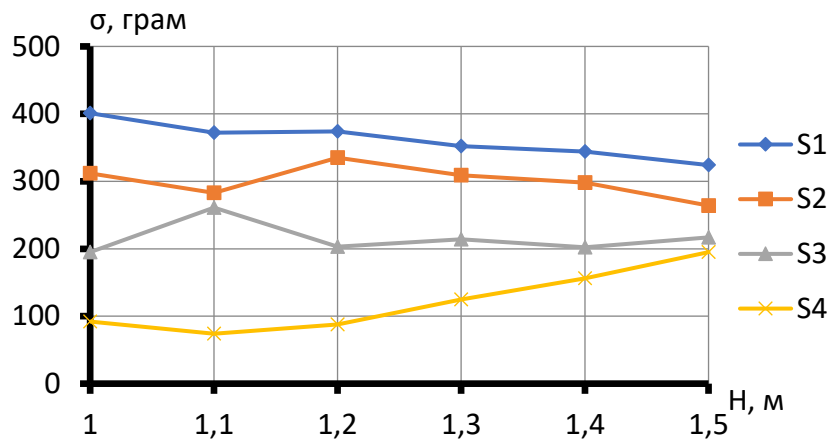


Figure 4.23 – Distribution of Wheat Grain Mass in the Container at a Discharge Height of 1.5 m

It can be seen from Fig. 4.23 that when wheat grain is discharged from a height of 1.5 m, a more or less uniform distribution of grain material over the entire area of the container is observed. Thus, when winter wheat grain was discharged from a height of 1.5 m, 324 g of grain was found in S_1 , 284 g in S_2 , 217 g in S_3 , and 195 g in S_4 .

The conducted studies show that the distribution of grain material over the bottom of a cylindrical container using a toroidal plate depends primarily on the grain discharge height and on the inclination angle of the toroidal plate generatrix to the horizontal. The best grain distribution over the bottom of a cylindrical container occurs when using a toroidal plate with a generatrix inclination angle of 12° to the horizontal, provided that the discharge height exceeds 1.5 m. When winter wheat grain is discharged using a plate with a generatrix inclination angle of 15° or 18° , a uniform distribution of grain is observed over the annular areas S_1 , S_2 , and S_3 . Such studies make it possible for practitioners to correctly install damping devices that reduce grain damage and its segregation.

CHAPTER 5. STUDY OF THE PROCESS OF LOADING SILOS WITH GRAIN MATERIAL

5.1 Methods of Loading Silos with Bulk Grain Cargo

5.1.1 Behavior of Bulk Grain Cargo During Silo Loading

When studying the operation of silo storage facilities installed at modern grain elevators, special attention should be paid to the development and design of devices by means of which grain cargo is delivered to silo inlets, discharged into cylindrical containers, and unloaded from them. At all stages of delivery and unloading of grain cargo, there are problems associated with damage to the kernels of the cargo and the formation of arches that impede the free outflow of grain from silos.

The main difficulties that arise during the operation of containers for bulk grain storage usually occur during the discharge of cargo from the container. Under the influence of various factors affecting this process, the discharge of cargo from the container becomes unstable and may stop completely. Such phenomena are caused by the following reasons [73, 78]:

- formation of static and dynamic arches above the silo outlet;
- during discharge, grain cargo may adhere to the silo walls, forming stagnant zones along the entire height of the container;
- the compaction pressure arising during the loading of tall containers leads to a sudden increase in pressure in the lower part of the container at the initial moment of grain discharge.

It is known that the stability of operation of cylindrical containers, especially tall ones, is affected by both internal and external factors. Internal factors include the physical-mechanical and biological properties of the bulk grain material, while external factors include environmental conditions, the structural and technological parameters of the containers, and the auxiliary devices installed on them.

The main factor influencing the operation of silos is the flowability of the cargo. The flowability of the cargo is classified according to fractional composition and shape. The presence in grain cargo of kernels with filamentous, needle-like, flake-like, and

plastic shapes promotes good mechanical interlocking of the kernels with one another, which leads to a deterioration in cargo flowability.

Moisture also significantly affects the flowability of bulk cargoes. As the moisture content increases, “liquid bridges” are formed between the particles, which enhance adhesion (cohesion) and capillary forces. This leads to material caking and deterioration of its ability to move freely. For fine-grained cargoes, there is a critical moisture limit. The most difficult-flowing (cohesive) grain cargoes are those with a moisture content exceeding 15–17%. In this case, the grain mass loses its flowability due to the increase in adhesion forces between grains [128].

The methods and modes of loading silos with grain material significantly affect the processes of grain storage and discharge, as well as the processed product itself. To ensure a non-damaging method of loading silos with bulk grain material, it is necessary to use special braking devices, the main part of which was considered in Chapter 3.

It is known that during the operation of loading devices, the bulk cargo interacts with the working elements of the device itself. Similar interaction occurs during the operation of various agricultural machines. The results of studies of these interactions can be applied in the design of both the loading devices themselves and the transport lines intended for delivering bulk material to silo inlets.

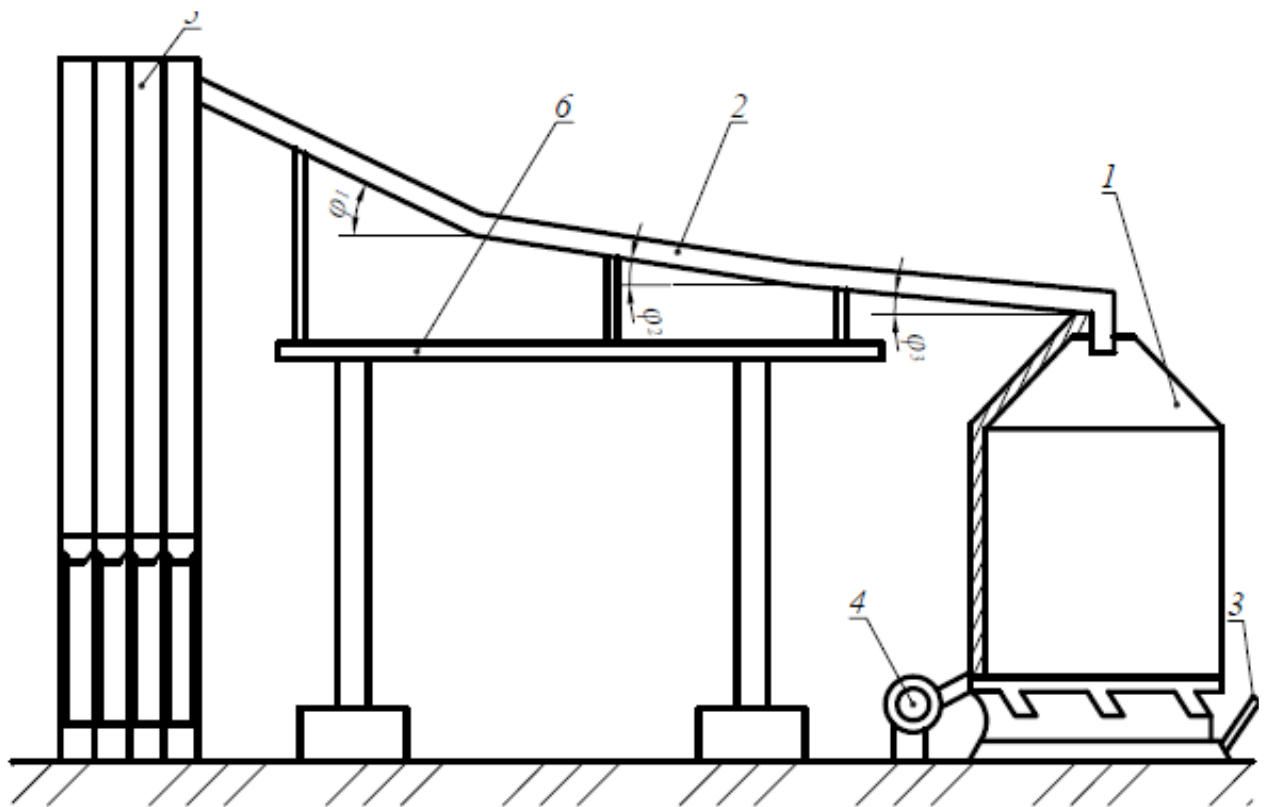
When studying the behavior of bulk cargo and its interaction with various metallic and non-metallic surfaces, the cargo is subsequently considered either as a continuous bulk body (continuum) or as a set of individual material points. As a rule, bulk cargo located in a closed container is represented as a continuous bulk body, while in free fall it is represented as a set of individual kernels [73].

5.1.2 Innovative Methods of Loading and Unloading Silos with Grain Material

Figure 5.1 shows a scheme of a grain elevator in which the silo is loaded by means of a gravitational installation. The main components of the grain elevator are: silo 1, gravitational loading installation 2, under-silo belt conveyor 3, active ventilation equipment 4, working tower 5, and supporting cascade metal structure 6 required to hold

the gravitational installation. The working tower houses bucket elevators, scales, grain-cleaning machines, gravity-flow and aspiration equipment, and other machinery.

The grain elevator operates as follows. Grain cargo from the working tower enters the accelerating section of the gravitational installation, which is inclined at an angle φ_1 to the horizontal. In this section, the grain cargo is accelerated to the maximum velocity $\vartheta_{\max}$, and at this velocity it enters the first braking section, which is inclined at an angle φ_2 to the horizontal. After passing the second section, the velocity of the grain cargo decreases by 10–15% of $\vartheta_{\max}$. The grain cargo enters the second braking section, which is inclined at an angle φ_3 to the horizontal, with a reduced linear velocity that gradually decreases. As the grain cargo approaches the silo inlet, the linear velocity corresponds to the standard value. This loading method eliminates the use of belt conveyors for delivering grain to the silo inlet, and as a result grain damage does not occur.



1 – metal silo; 2 – gravitational loading installation; 3 – under-silo belt conveyor; 4 – fan; 5 – working tower; 6 – cascade structure.

Figure 5.1 – Grain elevator with a gravitational-type loading installation

To improve the discharge of bulk material from a silo and eliminate such phenomena as stagnant zones, foreign inventors [127] proposed a new silo design consisting of one or several silo cells located adjacent to one another, thus forming a silo complex.

Each silo cell contains a body part forming the main volume for storing bulk material. The body part of such a structure has a rectangular cross-section and is bounded by vertical inner walls. In the lower part of the body there is a hopper part that connects the body part with the outlet opening. The hopper part has a transition funnel that ensures a gradual change in the cross-section of the internal space of the cell container from the cross-section of the body part to the cross-section of the outlet opening.

This silo design provides for a transition funnel formed by multiple transition elements made in the form of flat or curved plates. Such a design ensures a smooth transition between different geometric shapes and promotes uniform gravity-driven flow of the bulk material during its discharge from the silo.

5.2 Motion of Grain Cargo Along an Inclined Chute of a Gravitational Installation

The study of the motion of a material point was carried out by Galileo, Newton, Euler, and other scientists of classical mechanics. Further development of the theory of motion in relation to the tasks of agricultural machine engineering is reflected in the works of such scientists as P. M. Vasylenko [129], P. M. Zaika [14], and others. Papers [130, 131] present generalized material accumulated on this issue and provide methods for solving new problems in the theory of motion of material particles.

If the motion of a material point of weight G occurs by sliding with friction coefficient f_t along an inclined plane at angle α over a length L , with a level difference between the initial and final points $h = l \sin \alpha$ and velocities at these points ϑ_p and ϑ_k , then the work of the gravitational force of an individual particle, Gh , is spent on the work of friction and the increase in kinetic energy in accordance with the equation of the law of living forces [121]:

$$A_T = Gh = Gf_T \cos \alpha + \frac{G(\vartheta_k^2 - \vartheta_p^2)}{2g}. \quad (5.1)$$

If the initial velocity ϑ_p is known and the inclination angle α is specified, then the final velocity in the accelerating section of the gravitational installation will be:

$$\vartheta_k = \sqrt{2gh(1 - f_T \cot \alpha) + \vartheta_H^2}. \quad (5.2)$$

In a similar way, the final velocities in the braking sections of the gravitational installation can be determined.

5.3 Motion of Grain Kernels in the Gravitational Field of the Storage Facility

During the gravitational loading of silos with grain cargo, only gravity acts on individual kernels of the cargo, while at the beginning of their downward motion inside the silo they have an initial velocity corresponding to the minimum velocity at the end of the braking section of the gravitational installation. In the absence of loading-distributing devices and during downward motion along the corrugated sleeve, in addition to gravity, the kernels are also acted upon by the resistance force of the medium, which becomes significant for relatively light particles or particles moving at high speed.

The characteristic of individual kernels of the grain cargo entering the silo, by which one should judge the influence of air resistance on the nature of kernel motion, is the terminal velocity ϑ_v . In studying the motion of kernels in the air space, generalized indicators are used: the terminal velocity ϑ_v and the drag coefficient K_p . During the motion of kernels in the air space of the silo, they are acted upon by the force:

$$R = K \frac{\gamma}{g} F \vartheta^2, \quad (5.3)$$

where K is the drag coefficient;

γ is the specific weight of air;

F is the projected midsection area of the body;

ϑ is the relative velocity.

The acceleration received by individual kernels of grain cargo with mass m is expressed by the formula:

$$a = \frac{R}{m} = \frac{k\gamma F}{mg} \vartheta^2 = k_{\pi} \vartheta^2. \quad (5.4)$$

The terminal velocity is the flow velocity at which the kernel remains suspended, corresponding to the air-flow velocity.

The terminal velocity is determined by the formula:

$$\vartheta_B = \sqrt{\frac{Gg}{k\gamma F}} = \sqrt{\frac{g}{k_{\pi}}}. \quad (5.5)$$

If a grain has three different dimensions a, b, c namely length, width, and thickness, then the terminal (floating) velocity ϑ_B :

If a grain has three different dimensions a, b , and c , that is, length, width, and thickness, then the terminal velocity ϑ_v is:

$$\vartheta_B = \sqrt{\frac{\gamma l}{k\rho}}, \quad (5.6)$$

where $l = \sqrt[3]{abc}$ i $F = l^2$.

Of great importance in gravitational loading is the drag coefficient K_p , which depends on many unstable factors: the shape and roughness of the grain surface, the state of the air space, the air-flow velocity, and even the air temperature [90].

The drag coefficient is determined by the formula:

$$K_{\pi} = \frac{k\gamma F}{mg} = \frac{9.8}{\vartheta_p^2} \quad (5.7)$$

The value of coefficient K_p depends on the area of the projected midsection corresponding to a unit of gravitational force. With an increase in the relative area exposed to the flow, the drag coefficient, all other conditions being equal, increases. Table 5.1 presents approximate values of the air resistance coefficients K and drag

coefficients K_p for some agricultural crops stored in silos.

Table 5.1 – Values of coefficients K and K_p for grain of certain crops

Crop grain	Air resistance coefficient K	Drag coefficient K_p , m^{-1}
Wheat	0,184 – 0,265	0,075 – 0,120
Rye	0,160 – 0,220	0,100 – 1,140
Oats	0,118 – 0,150	0,169 – 0,300
Corn	0,180 – 0,260	0,050 – 0,060

5.4 Gravitational Installation with Three Channel Inclination Angles

The gravitational installation (Fig. 5.2) for studying grain motion consists of a hopper for storing grain material 1, a slide gate 2, an accelerating section 11 of the descent channel, a movable cylindrical hinge 4, two braking sections 3 and 5 of the descent channel, a fixed support 6 on which a screw carriage 7 is installed, elastic rods 8 connected in the upper fixed part of the installation to regulating devices 9 intended for raising and lowering the lower ends of the descent channel sections, and a hopper for collecting grain material 10.

The profile of the channel sections has the shape of a longitudinally cut cylinder turned with its open side upward [24]. The inner working surface of the channel has a certain level of roughness depending on the type of material of the sections.

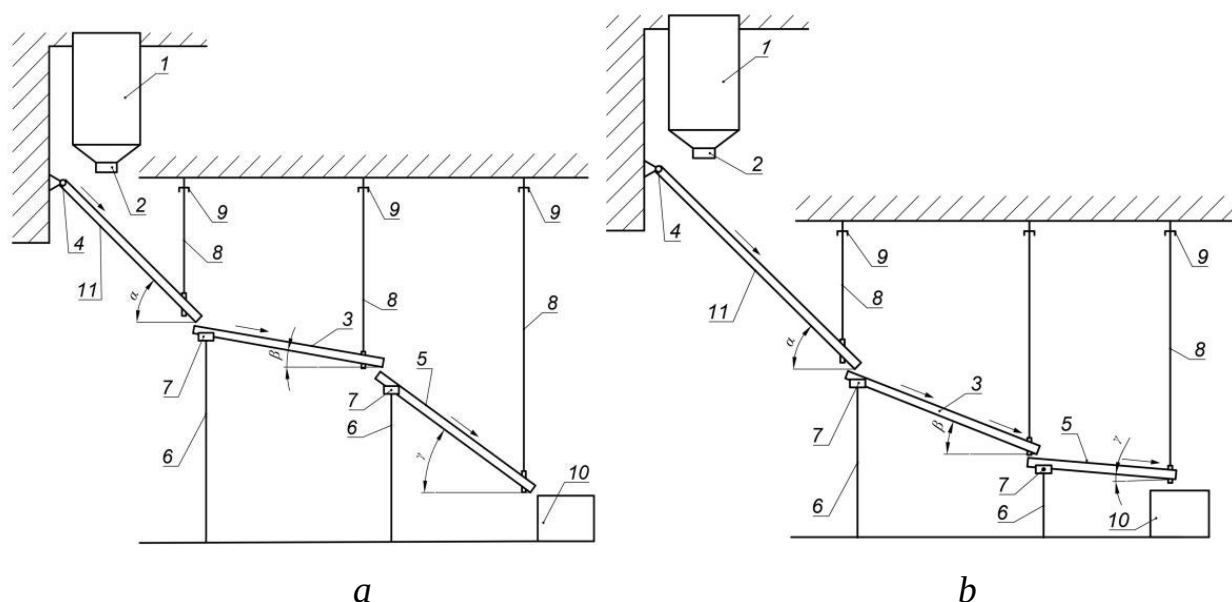


Figure 5.2 – Gravitational installation for studying the controlled motion of grain in the accelerating and two braking sections of a straight channel

The three channel sections are positioned in space by means of elastic rods 8, which are attached to the ends of the channel troughs and can change their length by means of regulating rods 9. The accelerating section near hopper 1 is attached to the wall by means of hinge 4. The braking channels are installed on one side on carriages 7, which can move up or down along the fixed supports 6. The accelerating section is set at angle α , while the braking sections are set at angles β and γ . Two variants of section arrangement are possible: $\alpha > \beta < \gamma$ (Fig. 5.2a) and $\alpha > \beta > \gamma$ (Fig. 5.2b). Grain falls from height h_0 , the height between the hopper and the beginning of the accelerating section, onto the upper part of the accelerating descent channel. In the braking sections, the grain slows down its motion. The discharge velocity of the grain acquires a value close to the initial velocity of grain motion along the accelerating section of the channel.

5.5 Mathematical Modeling of Grain Cargo Motion in a Gravitational Installation

The motion of grain along the accelerating and braking sections of the installation will be considered as laminar flow. During grain motion, a friction force arises between the chute surface and the outer layer of the grain mass; this force depends on the material of the channel and is determined by the sliding friction coefficient μ . It is assumed that

grain is discharged from the hopper uniformly and with the same velocity, that is, a steady flow takes place. According to the continuity equation $V \cdot S = \text{const}$, taking into account identical cross-sections of all three channels, we obtain the condition for ensuring flow steadiness: $V_{\text{init}} \leq V_{\text{fin}}$. To simplify further calculations, we shall assume that $V_{\text{init}} = V_{\text{fin}} = V_0$.

At the moment when the grain mass falls from the hopper outlet located at height h_0 above the edge of the accelerating section channel, the grain acquires the initial velocity V_0 . According to the law of conservation of energy,

$$mgh_0 = \frac{mV_0^2}{2}.$$

Moving along the accelerating section of length l_1 , inclined at angle α , the grain gains the maximum velocity V_{max} . In this case, part of the potential energy of the grain, $E_{p1} = mgl_1 \sin \alpha$, is converted into kinetic energy. Taking into account the work of the friction force

$$A_1 = \mu mgl_1 \cos \alpha,$$

we obtain the simplified equation for grain motion in the accelerating section:

$$\frac{mV_{\text{max}}^2}{2} = \frac{mV_0^2}{2} + mgl_1 \sin \alpha - \mu mgl_1 \cos \alpha$$

The motion of grain along the first braking section of length l_2 , inclined at angle β , occurs due to the previously acquired kinetic energy in the accelerating section and the action of gravity. In this case, the friction force acts more strongly because of the smaller inclination angle and causes a reduction in the grain velocity from V_{max} to $(V_{\text{max}} + V_0)$. Therefore, we obtain:

$$\frac{mV_{\text{max}}^2}{2} + mgl_2 \sin \beta - \mu ml_2 \cos \beta = \frac{m(V_{\text{max}} + V_0)^2}{8}. \quad (5.9)$$

The motion of grain along the second braking section of length l_3 , inclined at angle γ , occurs similarly to the previous section and ensures a decrease in grain velocity from $(V_{\max}+V_0)/2$ to V_0 .

To find the dependence between the inclination angles of the accelerating section and the two braking sections, α , β , and γ , let us solve the following system of equations:

$$\begin{cases} mgh_0 = \frac{mV_0^2}{2} \\ \frac{mV_0^2}{2} = mgl_1 \sin \alpha - \mu mgl_1 \cos \alpha = \frac{mV_{\max}^2}{2} \\ \frac{mV_{\max}^2}{2} + mgl_2 \sin \beta - \mu mgl_2 \cos \beta = \frac{m(V_{\max} + V_0)^2}{8} \\ \frac{m(V_{\max} + V_0)^2}{8} + mgl_3 \sin \gamma - \mu mgl_3 \cos \gamma = \frac{mV_0^2}{2} \end{cases} \quad (5.10)$$

From the second and third equations of system (5.10), we obtain:

$$\begin{aligned} \frac{mV_0^2}{2} + mgl_1 \sin \alpha - \mu mgl_1 \cos \alpha + mgl_2 \sin \beta - \mu mgl_2 \cos \beta &= \frac{m(V_{\max} + V_0)^2}{8} \\ mgl_1 \sin \alpha - \mu mgl_1 \cos \alpha + mgl_2 \sin \beta - \mu mgl_2 \cos \beta &= \frac{m(V_{\max}^2 + 2V_{\max}V_0 - 3V_0^2)}{8} \\ mgl_1 \sin \alpha - \mu mgl_1 \cos \alpha + mgl_2 \sin \beta - \mu mgl_2 \cos \beta &= \\ &= \frac{1}{4} \left(\frac{mV_{\max}^2}{2} \right) + \frac{1}{2} \left(\frac{mV_{\max}V_0}{2} \right) - \frac{3}{4} \left(\frac{mV_0^2}{2} \right) \\ mgl_1 \sin \alpha - \mu mgl_1 \cos \alpha + mgl_2 \sin \beta - \mu mgl_2 \cos \beta &= \frac{1}{4} (mgl_1 \sin \alpha - \\ \mu mgl_1 \cos \alpha) + \frac{1}{2} V_0 \sqrt{\left(\frac{mV_{\max}}{2} \right)^2} - \frac{1}{2} \left(\frac{mV_0^2}{2} \right), \\ mgl_1 \sin \alpha - \mu mgl_1 \cos \alpha + mgl_2 \sin \beta - \mu mgl_2 \cos \beta &= \frac{1}{4} mgl_1 (\sin \alpha - \\ \mu \cos \alpha) + \frac{1}{2} V_0 \sqrt{\left(\frac{m}{2} \left(\frac{mV_0^2}{2} + mgl_1 \sin \alpha - \mu mgl_1 \cos \alpha \right) \right)} - \frac{1}{2} \left(\frac{mV_0^2}{2} \right). \end{aligned} \quad (5.11)$$

Using equation (5.10) to simplify (5.11), we obtain:

$$\sin \beta - \mu \cos \beta = \frac{\sqrt{h_0^2 + h_0 l_1 \sin \alpha - h_0 \mu l_1 \cos \alpha - h_0}}{2l_2} - \frac{3l_1 (\sin \alpha - \mu \cos \alpha)}{4l_2}. \quad (5.12)$$

The right-hand side of equation (5.12) is a constant for a given angle α , initial grain falling height h_0 , and lengths l_1 and l_2 of the first and second sections of the device. Denoting it by b , we obtain an equation of the form $\sin \beta - \mu \cos \beta = b$. Let us represent this equation as:

$$(\mu - b)tg^2 \frac{\beta}{2} + 2 \tan \frac{\beta}{2} - (\mu + b) = 0.$$

$$\tan \frac{\beta}{2} = \frac{-1 \pm \sqrt{1 + (\mu^2 - b^2)}}{\mu - b}.$$

Taking into account that $\alpha, \beta \in [0; \frac{\pi}{2}]$, we have:

$$\beta = 2 \arctg \left(\frac{-1 + \sqrt{1 + (\mu^2 - b^2)}}{\mu - b} \right) + 2\pi k, \text{ where}$$

$$b = \frac{\sqrt{h_0^2 + h_0 l_1 \sin \alpha - h_0 \mu l_1 \cos \alpha - h_0}}{2l_0} - \frac{3l_1(\sin \alpha - \mu \cos \alpha)}{4l_2}. \quad (5.13)$$

Similarly, the dependence between the angles α and γ is found. Using the second and fourth equations of system (5.10), we obtain:

$$\begin{aligned} & \frac{m(V_{max} + V_0)^2}{8} + mgl_3 \sin \gamma - \mu mgl_3 \cos \gamma + mgl_1 \sin \alpha - \mu mgl_1 \cos \alpha = \\ & \frac{mV_{max}^2}{2}. \\ & mgl_3 \sin \gamma - \mu mgl_3 \cos \gamma \\ & + mgl_1 \sin \alpha - \mu mgl_1 \cos \alpha = \frac{3mV_{max}^2}{8} - \frac{mV_{max}V_0}{4} - \frac{mV_0^2}{8} \\ & mgl_3 \sin \gamma - \mu mgl_3 \cos \gamma + mgl_1 \sin \alpha - \mu mgl_1 \cos \alpha = \frac{3}{4}(mgl_1 \sin \alpha - \\ & - \mu mgl_1 \cos \alpha) - \frac{1}{2}V_0 \sqrt{\left(\frac{mV_{max}}{2}\right)^2} + \frac{mV_0^2}{4}. \end{aligned}$$

$$\begin{aligned}
& mgl_3 \sin \gamma - \mu mgl_3 \cos \gamma + mgl_1 \sin \alpha \\
& - \mu mgl_1 \cos \alpha = \\
& = \frac{3}{4} (mgl_1 \sin \alpha - \mu mgl_1 \cos \alpha) \\
& - \frac{1}{2} V_0 \sqrt{\left(\frac{m}{2} \left(\frac{mV_0^2}{2} + mgl_1 \sin \alpha - \mu mgl_1 \cos \alpha \right) \right)} + \frac{mgh_0}{2}. \\
& gl_3 \sin \gamma - \mu gl_3 \cos \gamma + \frac{1}{4} (gl_1 \sin \alpha - \mu gl_1 \cos \alpha) \\
& = -\frac{1}{2} \sqrt{gh_0} \sqrt{gh_0 + gl_1 \sin \alpha - \mu gl_1 \cos \alpha} + \frac{gh_0}{2}. \\
& l_3 \sin \gamma - \mu l_3 \cos \gamma + \frac{1}{4} (l_1 \sin \alpha - \mu l_1 \cos \alpha) = \\
& = \frac{1}{2} \sqrt{h_0^2 + l_1 h_0 \sin \alpha - \mu l_1 h_0 \cos \alpha} + \frac{h_0}{2}. \tag{5.14}
\end{aligned}$$

Separating the angles α and γ on opposite sides of equation (5.14), we obtain:

$$\sin \gamma - \mu \cos \gamma = -\frac{\sqrt{h_0^2 + l_1 h_0 \sin \alpha - \mu l_1 h_0 \cos \alpha}}{2l_3} + \frac{h_0}{2l_3} - \frac{l_1 \sin \alpha - \mu l_1 \cos \alpha}{4l_3} \tag{5.15}$$

Denoting the right-hand side of equation (5.15) by C , we obtain an equation of the form $\sin \gamma - \mu \cos \gamma = C$, which is solved by analogy with equation (5.12):

$$\gamma = 2 \arctg \left(\frac{-1 + \sqrt{1 + (\mu^2 - C^2)}}{\mu - C} \right) + 2\pi k,$$

where

$$C = \frac{h_0 - \sqrt{h_0^2 + l_1 h_0 \sin \alpha - \mu l_1 h_0 \cos \alpha}}{2l_3} - \frac{l_1 \sin \alpha - \mu l_1 \cos \alpha}{4l_3}. \tag{5.16}$$

The obtained equations (5.13) and (5.16) determine the dependence of the angles β and γ on angle α .

As follows from the obtained mathematical equations, the lengths of the accelerating and braking sections significantly influence the relationship between the inclination angles and the shape of the gravitational installation itself.

5.6 Calculation of the Geometric Parameters of the Gravitational Device

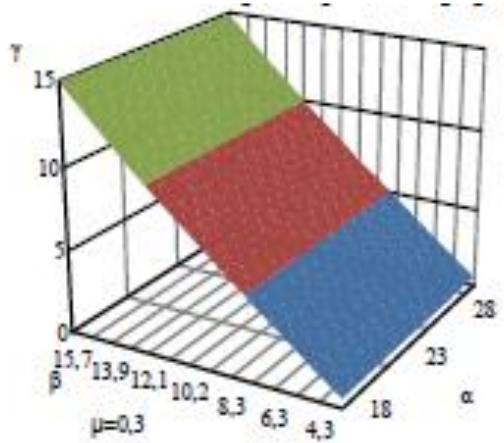
Using the equations presented above, the parameters of the gravitational device were calculated. This device prevents grain damage and premature discharge by determining the optimal inclination angles of the accelerating and braking sections in each particular case. Taking into account the final equations (5.13) and (5.16), an analysis was carried out of the character of variation of the inclination angles β and γ of the two braking channels under the variable change of the determining factors that form their values: α , μ , l_1 , l_2 , and l_3 .

During the study, the following ranges of variation of the influencing factors were taken into account: $\alpha=15\dots55^\circ$, $\mu=0.3\dots0.45$, $l=0.5\dots3$ m, $h_0=0.1$ m. The limits of the sliding friction coefficient μ were selected so as to take into account the entire range of its variation depending on the moisture level, the type of grain, and the type of material of the chutes of the gravitational device. The chute lengths were chosen according to two variants: the first variant, the length of the accelerating section should be equal to the sum of the lengths of the braking sections, that is, $l_1=l_2+l_3$ (Fig. 5.3); the second variant, all lengths are equal, $l_1=l_2=l_3$ (Fig. 5.4).

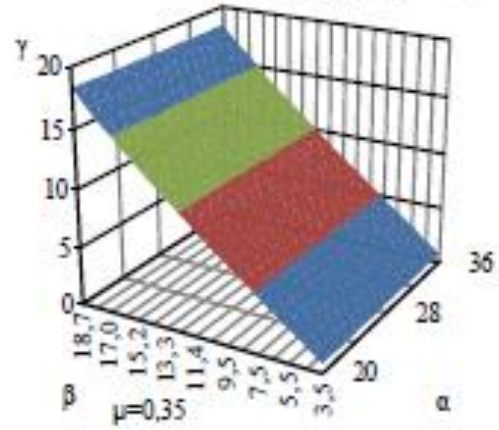
The graphical representation of the results of the analytical analysis of the character of variation of the inclination angles β and γ of the braking sections is presented in the form of a series of spatial response surfaces in Figures 5.3 and 5.4. All surfaces are characterized by a linear monotonic variation of the angles β and γ depending on angle α . A common characteristic of all the surfaces is a clearly expressed tendency for the angles β and γ to decrease with increasing inclination angle α of the accelerating section of the channel and with decreasing friction coefficient μ .

An increase in the inclination angle of the accelerating section and a decrease in the sliding friction coefficient cause an increase in the grain flow velocity, which leads to a linear decrease in the angles of the braking sections (Fig. 5.3a–d). This ensures that

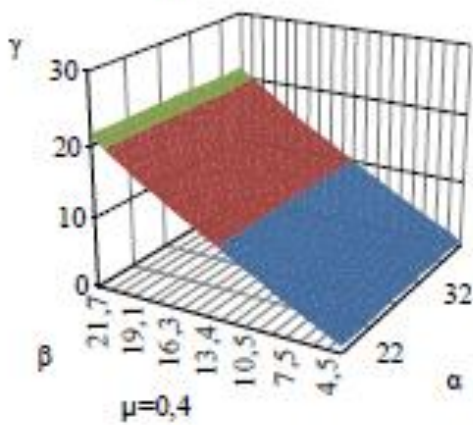
the grain discharge velocity from the gravitational device remains equal to the initial velocity of the grain flow when the grain falls into the accelerating channel. An increase in the braking effect on the grain flow, and hence a more gradual and less abrupt decrease in the angles β and γ relative to angle α , is achieved by increasing the sliding friction coefficient μ (Fig. 5.3), which may be implemented by changing the quality and roughness of the braking channel surface and by using different types of grain.



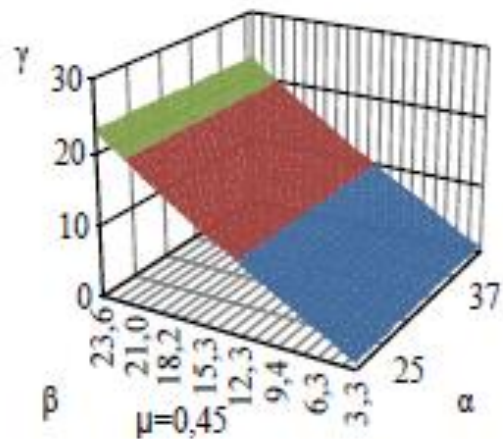
a



b



c

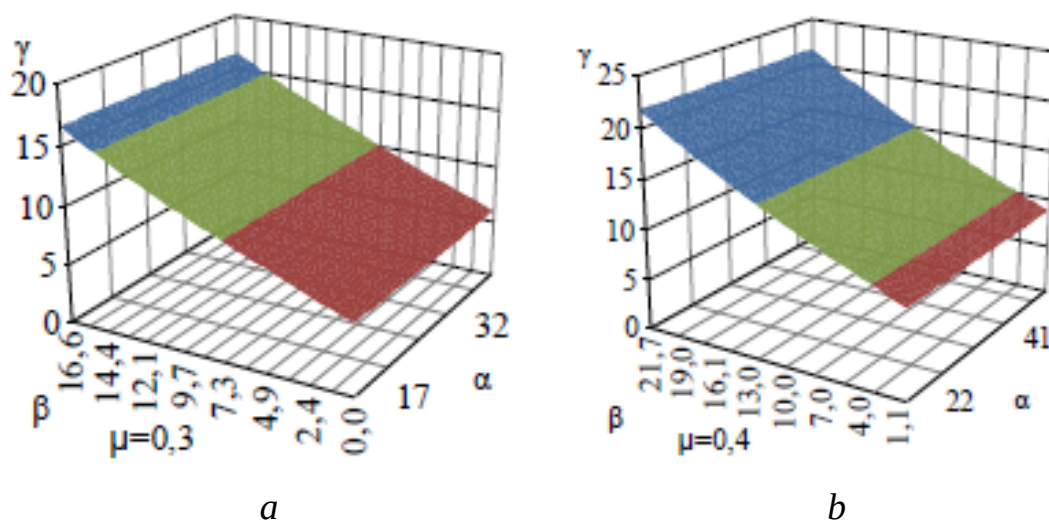


d

$l_1 = 3 \text{ m}$, $l_2 = 2 \text{ m}$ and $l_3 = 1 \text{ m}$: $a - \mu = 0,30$; $b - \mu = 0,35$; $c - \mu = 0,4$; $d - \mu = 0,45$

Figure 5.3 – Character of variation of the angles β and γ of the two braking channels with variation of the friction coefficient μ , the inclination angle α of the accelerating channel, and the values of the channel lengths

The study of the influence of the ratios of the lengths of the accelerating and braking sections on the angle values showed that under the condition $l_1=l_2+l_3$, the following inequality is satisfied: $\alpha>\beta>\gamma$ (Fig. 5.3), and the installation has the form shown in Figure 5.2b. Under the other variant, when $l_1=l_2=l_3$, the inequality $\alpha>\beta<\gamma$ takes place (Fig. 5.4), and the braking installation has the form shown in Figure 5.2a. The relationship in which $\beta<\gamma$ is explained by the need to increase the inclination angle γ in order to avoid premature stopping of the grain in the second braking section, which prevents its accumulation and premature discharge. This design feature regarding different variants of the inclination of the braking sections (Fig. 5.2) depends on the ratio of their lengths and may be used to satisfy different practical needs during the loading of grain into containers of various types.



$l_1=l_2=l_3 = 1 \text{ m}$: $a - \mu = 0,30$; $b - \mu = 0,40$

Figure 5.4 – Character of variation of the angles β and γ of the two braking channels with variation of the friction coefficient μ , the inclination angle α of the accelerating channel, and the values of the braking channel lengths

5.7 Study of Grain Cargo Motion in a Gravitational Installation with One Braking Channel

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To describe the mechanics of the grain flow, the gas dynamics theory in the form of the well-known Mendelev–Clapeyron law [93, 132] was used:

$$p(y)\bar{\varepsilon}(y) = \chi \left(\frac{du}{dy} \right)^2 \quad (5.17)$$

where $p(y)$ is the hydrostatic pressure, $\bar{\varepsilon}(y)$ is the average porosity of the grain flow, χ is a coefficient depending on the physical and mechanical properties of the grain material under study, and $\left(\frac{du}{dy} \right)^2$ is the square of the velocity of the moving bulk grain medium.

Since formula (5.17) includes dilatancy [93] (change in the volume of grain material under shear deformation) of the grain medium during shear, it is determined by:

$$\bar{\varepsilon}(y) = \frac{1}{1 - \varepsilon_0}, \quad (5.18)$$

where ε_0 is the porosity of the stationary grain layer ($\varepsilon_0 = \frac{V_n - V}{V_n}$, 0 where V_n and V are, respectively, the volume of the bulk grain layer and the volume occupied by the kernels of this layer).

The angle of installation of the accelerating chute is determined by the following formula:

$$\alpha_i = \arcsin \frac{BC}{AC}, \quad (5.19)$$

where α_i is the new installation angle of the accelerating chute, $AC=1200$ mm is the working length of the accelerating chute, and BC is the height of the lower part of the chute relative to the horizontal.

5.7.1 Methodology of Conducting the Experiments

In the experiments, seeds of such crops as wheat, corn, and sunflower were used. A batch of experimental seeds was weighed on electronic scales and poured into the

hopper of the installation. After opening the slide gate of the hopper, the time of movement of the grain material along the working surfaces of the chutes was recorded using a stopwatch. The experiment was repeated five times.

At the first stage, the time of movement of the grain material only along the working surface of the accelerating chute was studied. Initially, the accelerating chute was set at an angle $\alpha=26.4^0$ to the horizontal. At this angle, the movement time of wheat grain with standard moisture content was studied. Then, at the same angle, the movement of corn and sunflower seeds was studied. Having determined the average movement time of wheat, corn, and sunflower seeds at the fixed angle $\alpha=26.4^0$, it was necessary to change the installation angle of the accelerating chute. After changing the angle, the experiments were repeated sequentially. The new installation angle of the accelerating chute was determined according to formula (5.19).

At the second stage, the time of movement of the grain material simultaneously along the accelerating and braking chutes was studied. That is, the accelerating and braking chutes constituted one working element but with different inclination angles to the horizontal. In this case, the total length of such a chute was $l_z=2400$ mm.

The motion of grain along the accelerating and braking sections of the installation was considered as laminar flow with different layer velocities. From the continuity equation of the flow, and taking into account that the cross-sections of both chutes are identical, the condition for ensuring steady flow in both sections was obtained [106]. That is, the final velocity of the grain flow was not less than the initial velocity of this flow at the beginning of the accelerating section. This condition ensures the passage of the grain material through both sections without its accumulation in the braking section.

The accelerating chute of the installation had length $l_1=1200$ mm, and its installation angle α was chosen to be greater than the angle of repose of the grain material under study. The length of the braking chute was $l_2=1200$ mm, and the installation angle of this chute to the horizontal was set such that the following condition was satisfied: $\beta=(0.86...0.93)\alpha_i$. In the experiments, $\beta=0.92\alpha_i$. The angles of repose were taken as follows: for wheat $\zeta_p=25^0$, for corn $\zeta_k=32^0$, and for sunflower $\zeta_c=35^0$ [106].

At the third stage, experiments were carried out aimed at determining the density distribution function of the grain material in the direction parallel to the central axis of

the accelerating and braking chutes. For this purpose, a tray 4 intended for collecting the grain material flying out of the segment channel of the installation was placed at the threshold of grain discharge (Fig. 5.5). The tray consisted of five sections separated by partitions at a distance of 10 cm from each other. The height HHH of the tray installation relative to the horizontal was 30 cm, and the first compartment was located at some distance from the threshold of grain discharge. The working surfaces of the accelerating and braking channels had the same roughness, which ensured the limiting adhesion of the grain material to the segment-shaped bottom of the chutes.

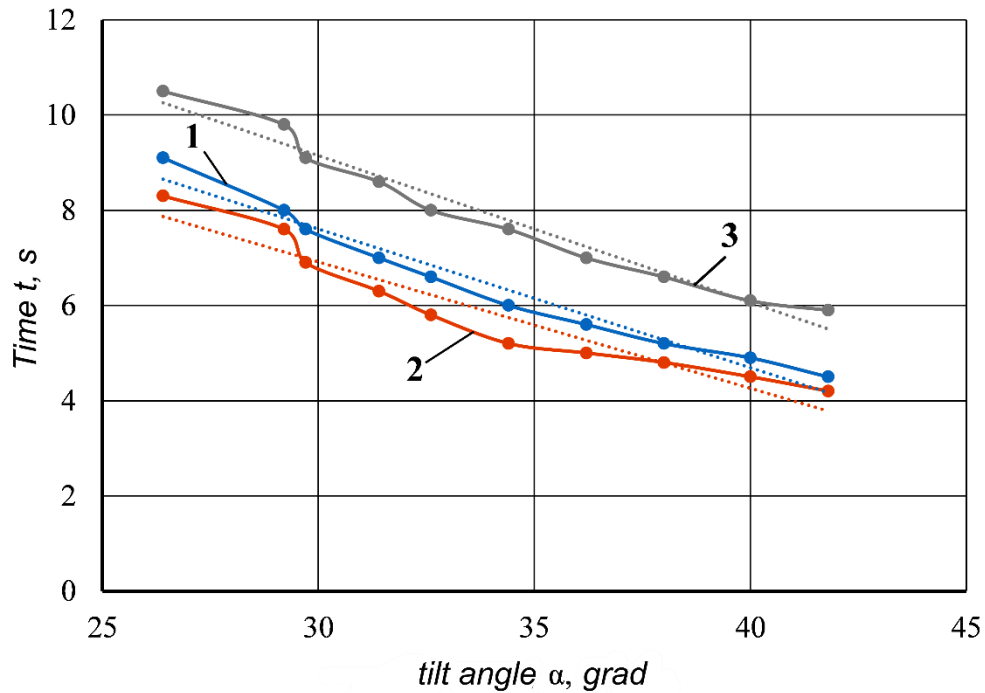
The experiments were carried out under conditions close to a steady laminar flow, which was achieved by setting the braking chute at an angle close to the angle of repose of the grain material under study.

The experiment was as follows. After setting the angle α of the accelerating chute, the angles β_1 , β_2 , and β_3 of the braking chute were successively set. After setting the angles α and β_1 , the grain material was loaded into hopper 1 of the installation. When the slide gate was opened, the grain material began to move from the hopper along the chutes and entered the compartments of the tray. After the movement of the grain along the accelerating and braking sections with angles α and β_1 had ended, the grain material taken from each compartment of the tray was weighed. In the first experiment, the inclination angles were $\alpha=70.4^\circ$ in the accelerating chute and $\beta_1=67.1^\circ$ in the braking chute.

Subsequent experiments were carried out in the same way, but the angle β was changed. Weighing the grain material in each tray compartment made it possible to determine the density distribution function of the grain material. In addition, the following experimental data were determined in this study: the height of the grain layer h at the threshold of its discharge into the tray, the width of the upper grain layer b , the time of filling of the compartments, the distance H between the discharge threshold and the tray, and the inclination angles α and β of the accelerating and braking chutes.

5.8 Results of the Studies

Figure 5.6 shows graphs of the dependence of the descent time of wheat, corn, and sunflower seeds along the working surface of the chute until their complete discharge on the installation angle of the accelerating chute relative to the horizontal. In this case, the mass flow rate of wheat supplied to the working part of the accelerating chute was $q_w=0.262$ kg/s, that of corn $q_c=0.244$ kg/s, and that of sunflower $q_s=0.286$ kg/s.



1 – wheat; 2 – corn; 3 – sunflower.

Figure 5.6 – Dependence of the descent time of grain material in the accelerating chute on its installation angle relative to the horizontal

After processing the experimental data, the following regression equations were obtained:

for wheat grain

$$t_w = -0.291\alpha + 16.33; \quad (5.20)$$

for corn grain

$$t_c = -0.265\alpha + 14.87; \quad (5.21)$$

for sunflower seeds

$$t_s = -0.308\alpha + 18.40. \quad (5.22)$$

The experiments established that the motion of grain material in the accelerating chute occurs as a continuous flow with a constant depth h . The movement time of the grain material depends on the installation angle of the accelerating chute relative to the horizontal. In addition, the descent velocity of the grain depends on the shape and mass of the kernels, the friction coefficient, and the material from which the chute is made. It was found that corn seeds descend the fastest from the chute, whereas sunflower seeds descend more slowly.

If the motion of wheat is studied simultaneously along the accelerating and braking chutes with different inclination angles to the horizontal, then the time of its passage along the working surfaces changes differently (Table 5.1). The lengths of the working surfaces of the chutes are equal.

Table 5.1 – Change in the movement time of wheat of standard moisture content in the accelerating and braking chutes ($l_1=l_2=1200$ mm)

Installation angle of the accelerating and braking chutes relative to the horizontal, deg		Time of passage of wheat seeds along the working surfaces of the chutes, s		Total movement time of wheat seeds, s
		Accelerating section	Braking section	
α	β	t_1	t_2	$t_{\text{сум}}$
35	32	6,0	8,2	14,2
37	34	5,5	7,1	12,6
39	36	5,1	6,5	11,6
41	38	4,4	6,3	10,7
43	40	4,2	5,6	9,8

It can be seen from the table that as the angles α and β increase, the descent time of wheat along the working surfaces of the installation decreases. To ensure slow descent of the grain material in the lower part of the silo, angle α should have the maximum value, whereas angle β should have the minimum value. For example, for wheat $\alpha=43^\circ$, and $\beta=32^\circ$.

When studying the motion of corn along the accelerating chute with an installation angle of $\alpha=70.4^\circ$ to the horizontal, followed by the transition of corn onto the braking

chute installed at angle $\beta=67.1^\circ$, it was found that the movement times along equal sections of the device differ. In the first accelerating section, the movement time of the grain material is 1.219 times greater than in the braking section. When angle β is changed to a new value of $\beta=63.8^\circ$, the movement time of the grain material becomes 1.328 times greater than in the braking section. As angle β decreases, a continuous increase in the segment profile of the grain flow is observed.

After loading 1.05 kg of sunflower seeds of standard moisture content into the hopper, the mass flow rate of seeds onto the accelerating chute was determined. With the hopper outlet diameter of 40 mm, it amounted to $q_s=0.286$ kg/s. After setting the accelerating chute at angle $\alpha=41^\circ$ and the braking chute at angle $\beta=38^\circ$, the movement time of the sunflower seeds along the working surfaces of the chutes was determined. The movement time was $t_1=7.1$ s and $t_2=10.3$ s, respectively. When $\beta \leq \zeta$, intensive braking of the grain flow occurs, and the grain completely fills the braking and accelerating channels, causing grain to spill over the chute edges.

The density distribution diagram of corn seeds in the direction parallel to the central axis of the braking chute is shown in Figure 5.7.

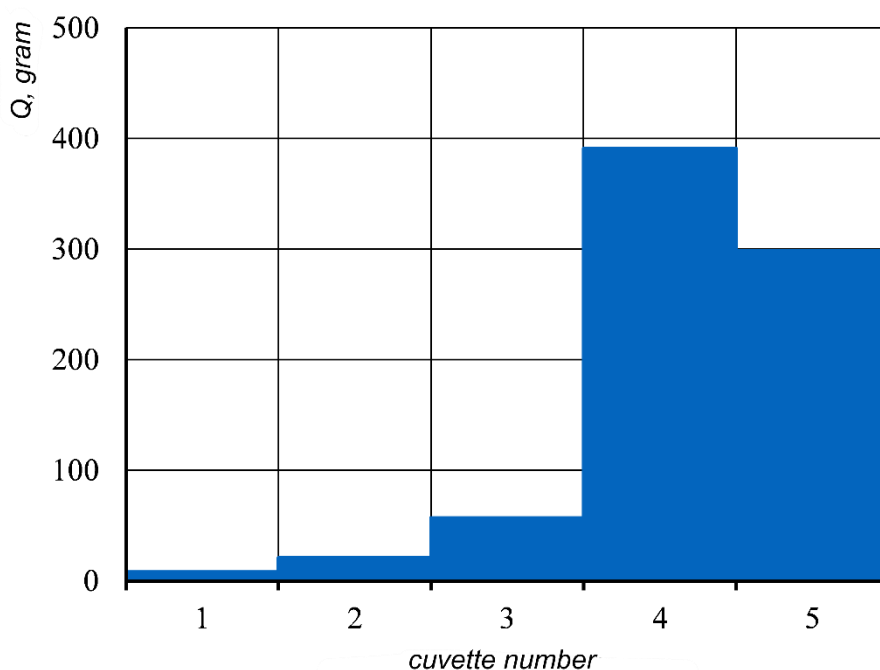


Figure 5.7 – Density distribution of corn seeds among the trays

It can be seen from the diagram that corn grain moving in the lower part of the chute at the threshold of discharge has the lowest velocity, that is, it falls into the nearest

compartments of the tray. Grain from the upper layers has a higher velocity, and therefore it falls into the farther compartments of the tray.

Thus, for the normal operation of a gravitational installation that can be used to load tall silo structures, with discretely varying inclination angles of the chutes relative to the horizontal, it is necessary that the inclination angles of the accelerating and braking chutes be greater than the angles of repose of the grain material under study. Moreover, it is desirable that the inclination angle of the accelerating chute be much greater than the angle of repose of the grain material. At the same time, the inclination angle of the braking chute should be 1.22 times greater than the angle of repose of the grain. A decrease in the inclination angle of the braking chute relative to the horizontal leads to intensive braking of the grain flow.

5.9 Deformation of Silos During Grain Unloading

The main types of loads acting on silos are static and dynamic loads. Static loads arise during filling and storage of grain cargo, whereas dynamic loads arise during its unloading from the container.

It has been found that the horizontal pressure on the bunker walls during unloading is significantly higher than the vertical static pressure. Therefore, all cylindrical metal silos are designed on the basis that internal force factors are distributed axisymmetrically (Fig. 5.8). At the same time, the weight of the grain presses on the silo wall nonuniformly, which negatively affects the entire operating process. It is necessary that the horizontal forces act uniformly on all sides, and that the silos be loaded and especially unloaded through the center of the container. This mode of silo operation is called “central flow.”

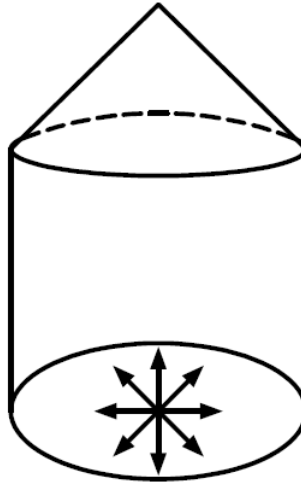
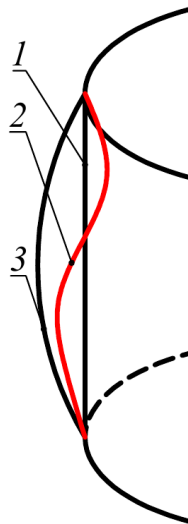


Figure 5.8 – Distribution of internal force factors on the walls of a cylindrical silo

“Central flow” is a flow profile in which a flow channel is formed in the grain heap through the discharge opening, while the bulk material in the zone between this flow channel and the bunker wall remains at rest.

In cylindrical metal silos, the pressure arising due to nonuniform outflow of grain product leads to the occurrence of a bending group of forces (Fig. 5.9) and results in skew-symmetrical deformation, which is the cause of loss of stability of the thin-walled silo shell.



1 – loading; 2 – empty silo; 3 – unloading

Figure 5.9 – Operating deformation of a silo during loading and unloading

The load on the foundation from a metal silo is 30% less than that from a reinforced-concrete silo; thus, the weight of a steel grain storage facility together with

the reinforced-concrete foundation amounts to about 35% of the grain mass [133, 134]. When designing silo structures, it is necessary to take into account that the load from the walls on the ring foundation, which consists of monolithic or reinforced-concrete structures, may in some cases make it advisable to use a ring pile foundation

CONCLUSIONS

The monograph presents comprehensive theoretical, analytical, and experimental studies of the process of safe grain loading into silos. The research addresses an important scientific and practical problem related to preserving grain quality during transportation, handling, and long-term storage. Under modern conditions, when grain production and export volumes continue to increase and requirements for maintaining its technological, food, feed, and sowing qualities become more stringent, the issue of minimizing mechanical damage during silo loading is of particular relevance. The results obtained in the monograph confirm that the loading stage is one of the most critical phases in the entire technological cycle of grain storage and that its improvement is a necessary condition for increasing the overall efficiency of elevator facilities.

The study establishes that traditional methods of loading grain into tall silos are accompanied by significant dynamic and impact loads, which lead to macro- and microdamage of kernels. Such damage reduces seed germination, worsens the technological and commercial properties of grain, intensifies respiration processes in the stored grain mass, increases heat and moisture release, and creates favorable conditions for self-heating and spoilage during storage. It has been shown that the main causes of grain damage are repeated contact of kernels with the working elements of conveying equipment, free fall from considerable height, impact interaction with the concrete bottom and walls of the silo, segregation of the grain mass, and compaction during filling. Therefore, ensuring gentle loading conditions is not only a matter of improving transport technology but also a key factor in maintaining grain quality and reducing quantitative and qualitative losses.

On the basis of the analysis of the physical and mechanical properties of grain, it has been demonstrated that the resistance of kernels to mechanical damage is determined by a complex combination of factors. Among the most influential are grain shape, size, mass, moisture content, elasticity, surface condition, bulk density, porosity, friction coefficients, and the internal structure of the kernel. The monograph shows that these properties significantly affect grain behavior during movement along transport routes and during impact interaction with technological surfaces. It has been substantiated that

the variability of these characteristics must be taken into account in the design and calculation of loading devices, since neglecting them leads to increased damage and reduced storage stability of grain material.

A substantial part of the research is devoted to the study of silo structures and the technological features of grain storage facilities. It has been established that metal silos are currently the most widespread type of grain storage structure due to their high degree of mechanization, compactness, automation, and efficiency. At the same time, despite their technological advantages, such silos remain highly sensitive to the problem of grain damage during loading, especially in the initial stage of filling when kernels fall onto a rigid base from a significant height. The study confirms that this problem cannot be solved solely by improving the operating modes of conveyors and elevators; instead, it requires the application of special loading-distributing devices installed inside the silo to reduce grain velocity and redistribute the grain flow more uniformly.

The monograph develops mathematical models describing the impact interaction of grain with rigid stationary surfaces, including the concrete bottom of a silo, and also models the interaction between individual kernels within a grain flow. These models made it possible to determine the main force characteristics of impact, estimate the magnitude of collision loads, and identify the conditions under which the probability of kernel damage increases. It has been proved that the impact energy and force acting on a grain kernel depend on the falling height, velocity before collision, grain moisture content, and the physical-mechanical properties of the contact surface. The obtained analytical relationships form the theoretical basis for predicting grain damage and for further engineering justification of gentle loading devices.

An important scientific result of the study is the theoretical substantiation of grain motion in gravitational loading devices designed to reduce the kinetic energy of the falling grain flow. In particular, mathematical models of grain motion in an open helical channel, on transfer shelves of a gravitational-cascade device, and along a toroidal working surface were developed. These models describe the relationship between the geometric parameters of the device, the inclination angles of its sections, and the kinematic parameters of grain motion. The research demonstrates that the use of channels with variable inclination angles and braking sections makes it possible to

control grain velocity at different stages of movement and thereby significantly reduce the impact loads acting on the kernels when they enter the silo.

The performed theoretical studies showed that a peripheral open helical channel with rationally selected geometric characteristics can provide a gradual decrease in grain velocity and create favorable conditions for gentle silo filling. At the same time, the variable geometry of the helical and cascade elements ensures a more controlled movement of grain material under gravity, reduces local concentrations of impact forces, and contributes to a more uniform distribution of grain inside the storage volume. This is especially important not only for reducing mechanical damage but also for preventing segregation, non-uniform packing density, and local zones of increased pressure in the grain bulk.

The adequacy of the proposed mathematical models was confirmed by experimental studies. The experiments carried out on model and laboratory installations demonstrated satisfactory agreement between theoretical calculations and measured parameters of grain motion. This proves the correctness of the adopted assumptions and the applicability of the developed analytical dependences to practical engineering calculations. The comparison of theoretical and experimental data confirmed that the proposed devices are capable of reducing the speed of grain flow and, consequently, the severity of impact interaction between kernels and silo surfaces.

The study of grain cargo motion in gravitational installations with one braking channel and with three channel inclination angles made it possible to improve the methods for determining the geometric and operating parameters of such devices. It was established that the introduction of braking sections into the trajectory of grain movement ensures controlled dissipation of kinetic energy without excessive grain accumulation or blockage of the channel. This makes it possible to improve both the technological reliability of the loading process and the quality indicators of stored grain. Thus, the monograph not only proposes conceptual technical solutions but also provides a scientific basis for their design and engineering implementation.

An important practical conclusion of the research is that the use of gentle loading devices can improve several technological indicators simultaneously. First, they reduce direct mechanical and impact damage to grain kernels. Second, they improve the

uniformity of grain distribution in the silo. Third, they reduce segregation of kernels by size and density, which is especially important for preserving the homogeneity of seed and food grain lots. Fourth, they decrease compaction and caking of grain mass, thereby improving aeration conditions and increasing the efficiency of active ventilation systems during storage. As a result, the implementation of such devices can contribute to preserving grain quality, extending safe storage duration, and reducing losses caused by spoilage.

The monograph also demonstrates that improving the loading process has a broader technological significance. Gentle loading should be considered as an integral element of the entire grain handling and storage system, closely connected with post-harvest treatment, transport operations, ventilation, unloading, and long-term preservation of grain quality. A rationally designed loading-distributing system not only performs the function of delivering grain into the silo but also influences the internal structure of the grain bulk, the distribution of pressures on silo walls and bottom, and the subsequent stability of storage conditions. In this regard, the proposed approaches are of value not only for silo engineering but also for the wider field of grain post-harvest technology.

The main scientific outcome of the monograph is the development of a holistic theoretical and methodological framework for the justification of gentle grain loading into silos. This framework includes the analysis of grain properties, mathematical modeling of impact interaction and grain flow motion, substantiation of the operation of special loading devices, and experimental verification of the obtained results. The practical value of the work lies in the possibility of using the proposed models and design recommendations in the modernization of existing elevator equipment and in the development of new silo loading systems.

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