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LOGISTICS OF BULK MATERIALS II – SPECIFICATION OF BASIC TASKS FAILURES  
OF BULK MATERIAL FLOW - VAULT FORMATION

LOGISTIKA SYPKÝCH HMOT II – SPECIFIKACE VÝCHOZÍCH ÚKOLŮ PORUCHY TOKU  
SYPKÝCH HMOT - KLENBOVÁNÍ

**Resume**

Aplikací logistického přístupu lze dosáhnout značných konkurenčních výhod, a proto je snahou provozovatelů a výrobců zařízení a technologií uplatnit skýtající konkurenční výhody.

V oblasti mechaniky sypkých hmot je poměrně často řešena problematika vzniku poruch toku materiálů v zásobnících, které se projevují přerušováním kontinuity toku sypké hmoty. V souvislosti se zásobníky sypkých hmot hovoříme zjednodušeně o klenbování zásobníku i když jev může souviset s celou řadou fyzikálních veličin a může být projevem komplexních souvislostí. Jedná se především o hledání souvislostí mezi vlastnostmi skladovaného materiálu, velikostí výpustného otvoru, tvarem zásobníku a materiálem, z kterého je zásobník vyroben.

V článku je uveden postup výpočtu polohy dynamické a statické klenby nad výpustným otvorem pro idealizované sypké hmoty, případně sypké hmoty vlhké a vazké. Uvedené rovnice jsou odvozeny pro mechanicko-fyzikální vlastnosti těchto dvou typů sypkých hmot a pro další typy je potřeba provést korekci na konkrétní mechanicko-fyzikální vlastnosti skutečné sypké hmoty. Jedná se především o sypké hmoty kompresibilní, směsi různých materiálů lišících se velikostí částic a jejich tvarem, případně specifickou hmotností, vytvořené jako směsi sypkých hmot několika typů.

Velmi podstatnou skupinou jsou sypké hmoty v oblasti velikosti částic v mikro a nano, kde vzniká složitá struktura elektrochemických, chemických, případně elektrostatických vazeb.

V článku je dále uveden principiální postup eliminace dynamické klenby, přičemž pozornost je zaměřena na řešení pomocí metody posunování dynamické klenby vyvíjené v Laboratoři sypkých hmot, VŠB – Technické univerzity Ostrava.

V tomto příspěvku je stanoveno optimalizační kritérium návrhu optimální dopravy především z hlediska mechanicko-fyzikálních vlastností sypké hmoty, nebo obráceně volba optimálních geometrických tvarů dopravní trasy, dopravníků a zásobníků na základě mechanicko-fyzikálních vlastností dopravované sypké hmoty.

Optimálně navržená doprava z hlediska nároků na konstrukci dopravních, skladovacích a úpravnických zařízení, to znamená plně funkční a ekonomická je jen ta, která stabilizuje vlastnosti dopravované sypké hmoty a vyloučí změny mechanicko-fyzikálních vlastností sypké hmoty po dopravních trasách. V tomto případě má tekoucí materiál polohu klenby ve stále stejné výšce nad výpustným otvorem. Na tuto skutečnost je možné zaměřit možnosti řešení a opatření vedoucích k eliminaci vlivu dynamické klenby na kontinuitu toku sypké hmoty.

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Jen taková doprava si může činit předpoklady na maximální ekonomický úspěch.

### **Resume**

*An immense technological advantage in economic competition can be achieved by using methods of logistics and that is why the operators and producers of equipment and technologies processing bulk materials make an effort to apply the right and profitable procedures.*

The bulk material research solves relatively frequently problems connected with flow failures in bulk material containers, which present themselves in interruptions of flow continuity. The events of formation of bulk material vaults in silos are the most common causes of the failures. These phenomena depend on various physical characteristics of flow processes and have a quite complex character. The relevant factors are especially properties of stored materials, dimensions of outlet openings, silo shapes and qualities of silo wall materials.

The paper presents terms for a computation of the positions of a dynamic and static vaults above outlet openings for idealized bulk materials or wet and viscous bulk materials respectively. The formulae given below were derived with respect to mechanical and physical properties of these two bulk material categories. Appropriate corrections with respect to specific mechanical and physical properties must be done for other types of real bulk materials. Those are mostly compressible bulk materials, mixtures of various materials differing in dimensions and shapes of particles or in their bulk densities.

Bulk materials having particles of micro- and nano-dimensions form a quite numerous group as well. A quite complex structure of electrochemical, chemical or electrostatic bonds is typical for this group.

The paper shows a principal procedure for an elimination of formation of dynamic vaults. The method we focused on is a shift of a dynamic vault. The solution of this problem is pursued in the Laboratory of Bulk Material, VŠB - Technical University Ostrava.

An optimization criterion for a transportation of bulk materials meeting specific requirements to their mechanical and physical characteristics or for a selection of optimum geometrical shapes, transport routes, conveyors and containers based on mechanical and physical properties of transported material in reverse is formulated here.

An optimum project of a bulk material transportation, i.e. its constructional, transport, storing and processing aspects, means fully functional and economic transport that stabilizes properties of transported bulk material and eliminates changes of its mechanical and physical properties along its transport route. With respect to this formulation a stabilization of a vault position of flowing material above an outlet opening of a container is expected. This demand is a key point for ensuring a continuity of bulk material flow. Measures and solutions must focus on an elimination of an impact of dynamic vault on the flow continuity and thus form a condition for a maximum economical profit.

### **Key words**

:bulk material, *mass* flow, vault formation, flow failure

## **1 Introduction**

Elements reducing transport cross-section in the direction of bulk material movement are very frequently designed in the industry of production, transportation and storage of bulk materials. It can be expected with a high probability that such segments of transportation routes become a sure source of flow failures. The flow cross-section narrows down there, the bulk material is pushed-in into a smaller space - usually without an adequate increase of material velocity to conserve its original flow density and mechanical and physical properties. The narrowing of the reduction element causes an increase of the bulk density and deteriorating of material flow characteristics, even an interruption of flow continuity. Containers, shifting sand, changes of mechanical principles of conveyors along transport routes and other problematic issues can be mentioned as examples.

Technical practice and scientific research focused on these phenomena in applications but it can be said that the attitude to this problem is more or less empirical one - no deeper generalization of laws governing these processes was found.

Therefore it is searched for relations between construction parameters of transportation routes - that is narrowing transport profiles, construction of route segments, narrowing parts of containers and used materials). These characteristics are related to the angles of internal friction of bulk materials and governing laws and rules allowing a mass flow in narrowing elements of transport routes are searched for specialists.

This text presents the standard approach to the problem; it takes into account dimensions and shapes of outlet openings and changes of mechanical and physical properties of bulk materials - represented by the angle of internal friction - and their influence on a formation of vaults is searched. The influence of the size and shape of an opening on the position of bulk material vault within technical work is described. These relations are not taken into account in most of applications with an intention to allow for conveyors with a small-occupied space, a small transport cross-section and with relatively high transport velocities. Such reduced solutions seem to be favorable in preparation and pre-project or offering phases. Nevertheless an improperly designed and selected transport technology amend to operating cost in the first years of work and this additional cost surmounts the seeming spared means.

## 2 Static and dynamic vaults

The relation between the size and shape of the outlet opening (for model bulk material) and a position, shape and main semi-axes of dynamic vaults was derived in the Laboratory of Bulk Material, VŠB-Technical University Ostrava [1,3] some time ago. The definitions of bulk material characteristics which were used for the derivation of these laws are given in [2].

### 2.1 Static vault

The static vault arises within the regime of the piston flow mechanism. This type of flow mechanism is caused by the funnel flow.

The constant of the flow profile of the piston flow mechanism can be obtained as

$$Z_1 = \frac{D}{2.S} k.f . \quad (*1)$$

The height of the static vault above an outlet hole is given by the term

$$H1 = \frac{1}{Z_1} . \quad (2)$$

### 2.2 Dynamic vault

The dynamic vault arises within the regime of the shell flow mechanism. This shell mechanism allows for a mass flow in case suitable construction parameters are used (geometry and material of equipment is meant).

The constant of the flow profile of the shell flow mechanism can be obtained as

$$Z_2 = \frac{\pi.D}{2.S} k.f . \quad (3)$$

The height of the dynamic vault above an outlet hole is given by the term

$$H2 = \frac{1}{Z_2} . \quad (4)$$

### 2.3 Graphs of the relevant functions

The Figure 1 shows the positions of static (a) and dynamic (b) vaults as functions of the outlet diameter  $\varnothing D$  and the angle of internal friction  $\varphi_e$ . To present a more illustrative case the functions correspond to „the ideal bulk material“ [2,3] - a material with the angle of internal friction depending primarily on space arrangement of particles. The value of the angle is fixed to the same height of bulk material where the angle remains relatively constant (dry or wet sand can represent a practical example of such material). Stronger functions of wetness, electrostatic forces and other aspects appear with other types of materials. It leads to deformations of curves of vault heights even with a constant outlet dimension and to individual or even multiple local extremes - depending on prevailing influence (particle shapes, bonds and other aspects).

An applicability domain of the ideal bulk material model must be specified and demarcated in case of a complex composition and structure of some real bulk material - a mixture consisting of more components for example with differences in densities, chemical composition, shapes and size of particles and with other departures. It means to summarize additional partial works because they can become dominant and surmount the fundamental work loss.

Figure 1(c) shows the position  $H1$  of the dynamic vault above the outlet opening and  $H2$  the position of the static vault above an outlet opening depending on the angle of internal friction and the diameter of the outlet opening. The position of the two flow profiles relative to the container walls is of great importance too - flow profiles can be inside the container, they can touch the container walls or even the container can be inside the flow profiles.

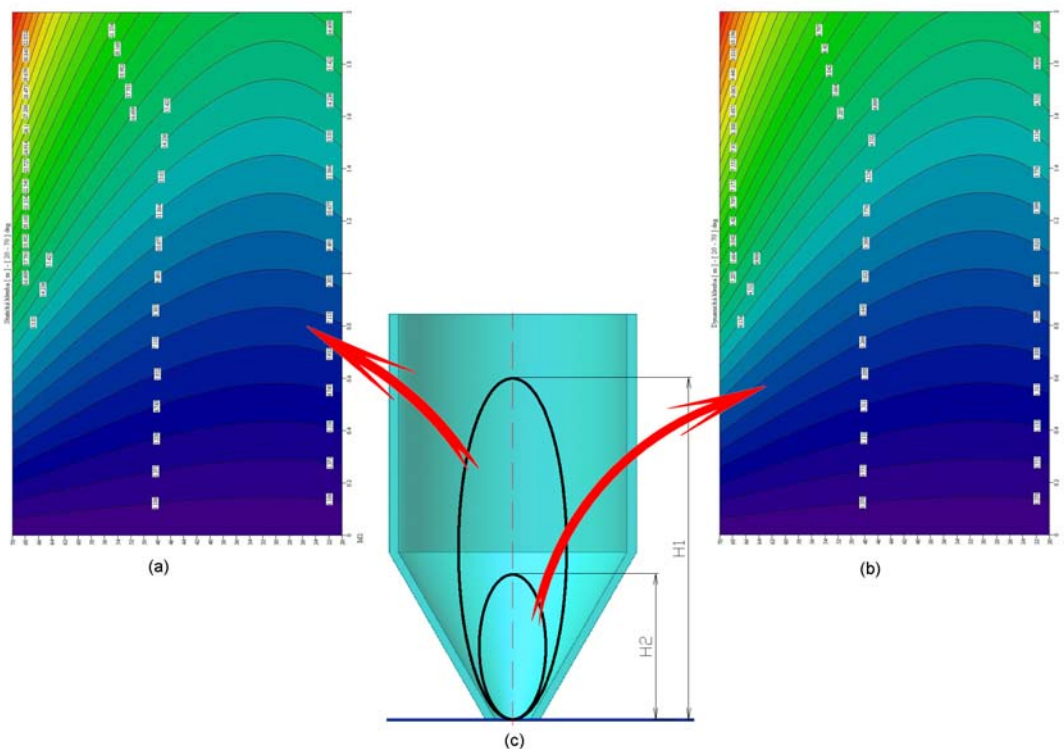


Figure 1 The heights of the static (a) and the dynamic vault (b)  $H_{1,2} = f(\varnothing D, \varphi_e)$  as functions of the outlet diameter  $\varnothing D$  and the angle of internal friction  $\varphi_e$ .

## 2.4 Modeling of static and dynamic vaults in practice

The vaults appear quite frequently in technical practice. Actually they are not failures in the actual sense of the word, but exhibitions of physical nature of the bulk material flow not respected by engineers. The exhibition of the physics causes the failures of flow continuity!

To clarify the problem an exemplary practical situation occurring in a hall of large-volume silos storing clinker for cement works is described here. The problem consists in drops of static vaults. Large quantities of dust evolve and pressure pulses repeatedly bump on a container structure. The spontaneous evolution of dust causes that the capacity of filters is not sufficient enough to trap the dust. Clinker dust fractions enter the dust separating circuits, that are not able to process the surplus of material, the de-dusting system is choked up and drops out. The Laboratory of Bulk Materials of VŠB - Technical University Ostrava undertakes task research to solve the problem because similar events are of ever increasing importance.

The following photos show a simulation of a large-volume container of clinker. The model is formed by two vertical glass plates with a sample of clinker between them. Clinker flows towards adjustable outlet openings. The photo in Figure 2 verifies positions of two types of vaults. The dynamic vaults were formed above outlet openings and the static vaults were formed above the first ones.



**Figure 2** Simulation of the static and the dynamic vault above an outlet opening for the flow of clinker; a situation prior a drop of a static vault [7],  
VŠB - Technical University of Ostrava, 2004



**Figure 3** Simulation of the static and the dynamic vault above an outlet opening for the flow of clinker; a situation after the drop of the static vault [7],  
VŠB - Technical University of Ostrava, 2004

The Figure 3 shows the photo of the model after the static vault dropped down. The drops of static vaults cause dynamic pressure pulses and appearance of large amounts of dust. The pressure pulses have a negative impact on a container structure - they can damage it or even destroy it and endanger the safety of a workshop. With some material exists a threat of ecological catastrophe.

### **3 Design of the contraction profile of container chute**

#### **3.1 The relation of the contraction container chute and a successive transport equipment**

Because of economic reasons an operator of a transportation equipment usually wants to have conveyers of small dimensions. Their low transportation capacities require containers with the smallest possible outlet openings. The Figure 4 item (a) shows the optimum solution of a container outlet opening and a conveyor construction. In case the equipment operates safely - especially with suitable bulk materials not causing any problems - a minimum cost of the transport junction operation is achieved too.

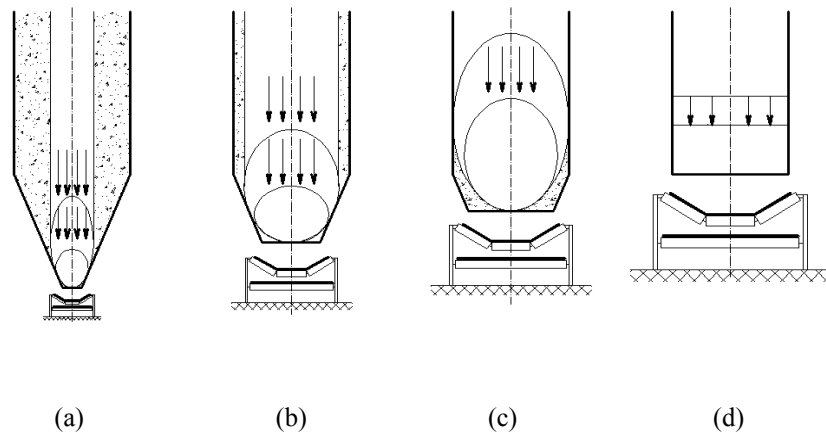


Figure 4 Relation of the outlet opening and a successive transportation equipment

The item (a) of Figure 4 represents the optimum design of a container with respect to the operation cost. This construction however can cause and usually leads - with prevailing number of real bulk materials - to the funnel flow and to a formation of vaults in the container. An elimination of the funnel flow and resulting vault appearance is achieved by an extreme geometrical arrangement shown in Figure 3 (d). The cost of the container construction and of its operation is the largest one however such arrangement ensures a continuous bulk material flow. A negative feature of such solution is conveyors of large dimensions and low transport velocities. Such large conveyors however mean a heavy load on building floors. The costs to strengthen building structures must be accounted for.

### 3.2 Design of a container contraction segment with a passive element

The application of a passive element in the position of the dynamic vault causes that the vault moves to the upper part of the container and eliminates unfavorable effects of its existence. The position of such passive element must be found to achieve a continuous mass flow in the container.

The flow profiles are moved to the vertical part of the container and flow similar to the Figure 3 (b) or Figure 3 (c) arises.

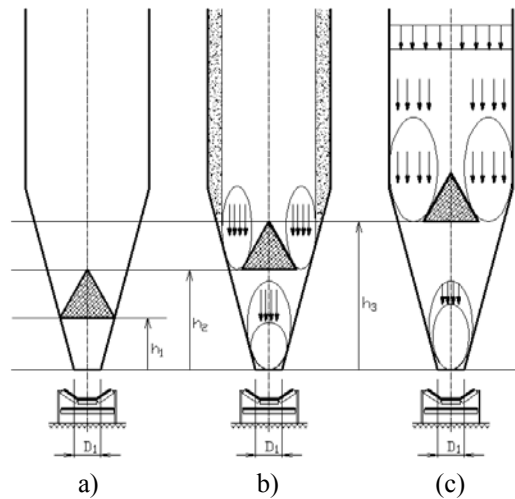


Figure 5 Relation of the container contraction chute with a passive element and a successive transportation equipment

### 3.3 Evaluation of the dynamic vault position - example

The article [2] presents the ideal bulk material that can be used for tests giving results corresponding to laws of bulk material motion as in [4,5,6]. The results of these tests can be used as standards for experiments with real bulk materials.

The position of the dynamic vault above an outlet opening can be found by setting the diameter of the outlet opening.

#### Numerical example

An assumption is made that the angle of internal friction is constant (the ideal bulk material [2],  $\varphi_e = 30^\circ$ ) and heights of dynamic vaults for two different dimensions of an outlet opening are found.

1. For an opening of  $\varnothing D_1 = 0.5$  m the position of the dynamic vault is  $H_2 = 1.296$  m above the outlet opening.
2. For another diameter  $\varnothing D_1 = 1.5$  m the position of the dynamic vault is  $H_2 = 3.8$  m above the outlet opening.

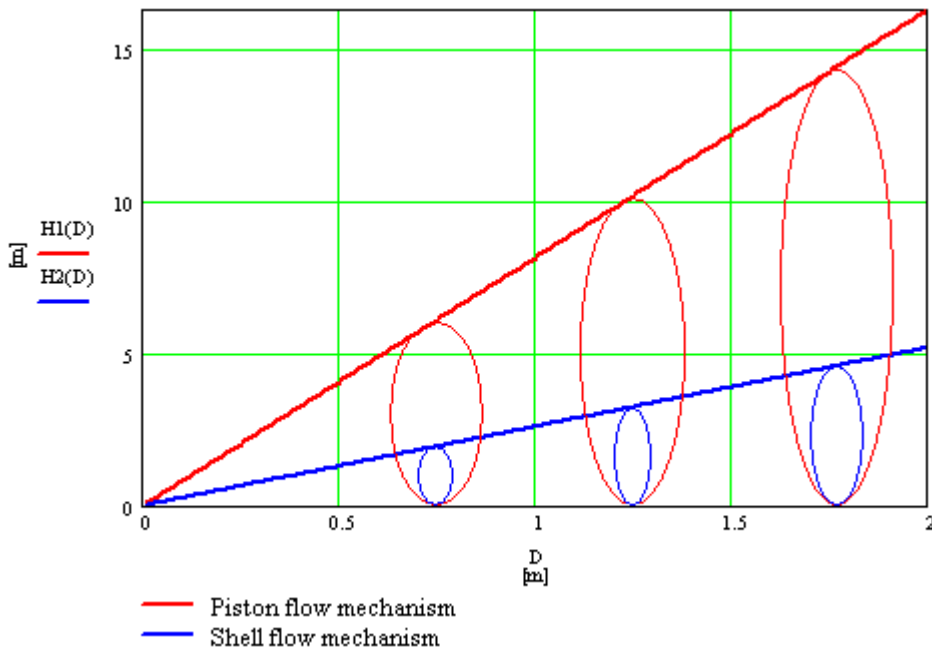


Figure 6 Position of static and dynamic vaults above an outlet opening as a function of the outlet opening diameter; the angle of internal friction is taken constant

Figure 5 offers a scheme for shifting the dynamic vault by means of a passive element. By placing the passive element at height  $h_2$  or may be  $h_3$  the dynamic vault is moved to the vertical part of the container. This does not allow the vault stabilization and fixing it on the container body.

Figure 6 depicts a dependence of flow profiles size of Piston (red color) and Shell (blue color) flow mechanism on a circle outlet size in the range from 0 meter to 2 meters. The relation is provided for ideal properties of bulk solids, i.e. a constant angle of internal friction and a constant ratio of radial to axial stress. Especially, ideal properties of bulk solids are characterized by an enlargement of shell and piston flow mechanism size with the outlet surface size proportionally. The assumption does not have to be valid legitimately for bulk solids that do not execute initial conditions.



#### 4 Conclusion

Methods of logistics applied to processing of bulk materials initiated basic paradox when searching for optimum relations between operation costs, investments, information and financial flows on one side and mechanical and physical characteristics of bulk materials or materials used for construction of transport, processing and storage equipment on the other side.

Practice and experience suggest that current classical attitude to production, transport and storage of bulk materials must be completed by new solutions that take into account both technical and economical points of view and other aspects.

The first paradox consists in relation of a container and transport routes:

- A. The optimum outlet opening of the container (as far as bulk material concerned) is a such one when no reduction of transport cross-section profile along the transport route occurs. That means that the transport route should have a cross-section large enough and constant (or it may even increase).
- B. The optimum construction and economical aspects require minimum construction dimensions of a conveyer. To ensure the continuity of a specified amount of bulk material higher transport velocities are expected - the transport has a dynamic character. Mass of transport routes and technologies represents a lower load for constructions and buildings and the routes and technology occupy a smaller space.

The main optimizing logistic requirements on construction of containers and transport routes within the current technologies can not be concurrently satisfactorily met. When reviewing nowadays technology the logistic optimization incorporating parallel economical, operation, construction a material aspects seems nearly impossible.

The optimizing of container construction by focusing on mechanical and physical characteristics of stored bulk material means a selection of outlet opening of large dimensions or application of additional and complex constructions (insertions) producing a requirement of more demanding design and higher operation cost.

Selection of the dimensions of an outlet opening of a container usually needs a reduction of a chute to the dimensions of a successive conveyer and thus an insertion of a reductive element.

A formation of bulk material vaults in containers is the natural phenomenon of a bulk material flow. The continuity of the material flow is periodically suspended in the position of a dynamic vault. A probability of a dynamic vault formation increases if some unsuitable relation between outlet opening dimensions and geometry of container walls was selected. The dependence of the vault height on the size of outlet opening is of a more general character. The factors involved are for example wetness of bulk material, chemical or electrostatic bonds and other aspects. A reduction of negative impacts of the vault formation can be achieved by positioning of a passive element in the place of the original dynamic vault. Bringing some appropriate form of energy to this place and thus reducing the angle of internal friction to increase the material fluidity is possible too.

It is apparent that introduction of method of logistics into technology, transport and storage of bulk materials is required to optimize economical, constructional, operation and other aspects of the problem.

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## Nomenclature :

$\varnothing D$	a diameter of an outlet opening
$k$	$k = \frac{1 - \sin \varphi_e}{1 + \sin \varphi_e}$ a yield coefficient
$\varphi_e$	an angle of internal friction
$f$	a tangent of the angle of internal friction
$Z_1, Z_2$	constants of flow profiles of piston and shell flow mechanisms
$H_1$	the height of static vault above an outlet opening
$H$	the height of dynamic vault above an outlet opening
$S$	an area of an outlet opening
$h_1, h_2, h_3$	positions of a passive element above an outlet opening

**Recenzent:** prof. Ing. Karel Bailotti, CSc.

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