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The "Bins & Bunkers Research Group" at the Technical University Clausthal

W. Dreyer, Germany

Die Forschungsgruppe "Silos & Bunker" an der T. U. Clausthal
Le groupe de recherches «Silos et tremies» à l'Université de Clausthal
El grupo de investigación «Silos y Depósitos» en la Universidad Técnica de Clausthal
クラウハウ工業大学の「ビン・バンカー研究グループ」
克劳斯索尔技术大学“贮存仓库研究小组”
«بنز آند بنكرز ريسيرش جروب» في جامعة كلوثال الفنية

1. Introduction

The Bins and Bunkers Research Group at the Department of Mining at the Technical University Clausthal, Federal Republic of Germany, was established in 1955. Since that time its main activities have covered and have been mainly centred around the following six aspects of bulk solids handling:

- Flow behaviour of bulk solids
- Design of hoppers, bins and bunkers
- Segregation phenomena relating to the storing of bulk materials
- Load calculations and measurements in hoppers and bunkers
- Determination of discharge quantities from storage
- In-bin blending and the use of flow-corrective inserts in hoppers and bins.

In almost every branch of the processing industry it is necessary at some stage in each process to store bulk materials in devices such as hoppers and bunkers. The movement of bulk material discharged from hoppers and bunkers is typically irregular and the amount of particle to particle segregation which occurs is dependent principally on the hopper shape, the type and size of the outlet and the physical and chemical characteristics of the stored material. General design considerations concerning these matters are given by H. Wöhlbier [27, 28] and Reisner [12]. An excellent survey of the state of research relating practical design and techniques based on flow properties of bulk solids is given by Reisner and von Eisenhart Rothe [18].

2. Bulk Solids Flow

Investigations on some factors influencing the behaviour of granular materials discharging from bunkers were reported by Hampel [1]. The formation of a cone during the filling of a bin causes bulk materials to segregate. Hampel [1] showed that bins empty first through the centre of the stored mass where the fine material is located and then from the sides, where the coarser particles are located. Reisner [12] describes similar kinds of containers for the storage of granular materials of different grain sizes ranging from fine powders to large particles. The pattern of movement when filling or emptying the container is the same whatever the particle size and can only be changed by alternating the dimensions of the bin, the aim being of course to design the bin to suit the particular stored material. Theoretical and experimental studies over the last few decades have done much to promote a better understanding of material behaviour, and today, with a wide demand for silos of ever-increasing capacity, the results of such studies are of paramount importance.

The most frequently applied method to identify the flow-zones within bunkers is to fill the device with layers of different colours. Free-flowing solids have a flow pattern which cannot be defined exactly either as mass flow or core flow. The stored mass is activated so that motion takes place also at the walls. Reisner [15] details the problems, studies and results relating to the flow of bulk materials in a hopper, bin, bunker, or silo. Because of varying discharge rates for materials with spherical and non-spherical particle shapes a dimensionless factor was developed to represent the figure by which the mean *efflux rate* for an ideal bulk material should be multiplied to obtain the *efflux rate* for the bulk material under investigation. Due to the influence of internal friction, the void ratio and bulk density for different materials were investigated. Experiments were made to determine the variables affecting the angle of friction of dry granular materials [16]. Also investigated were function parameters of different conical bottoms, which are of importance for steeper inclinations [16].

Detailed design of bulk handling and storage facilities should take into account the flow properties of the bulk solid to be stored. In order to provide bulk handling operations with trouble-free flow and no process stoppages or interruptions, it is necessary to evaluate initially the handling characteristics of the materials in quantitative terms and then to relate these to each conveying and storage function during processing. Bulk solids may even change their flow characteristics during processing and this also could affect subsequent handling operations.

Von Eisenhart Rothe and Peschl [25] showed that one of the most important mechanical properties related to the flowability of a bulk solid is its internal shear strength. The larger the shear strength, the more difficult it is for the bulk solid to flow. Various types of shear testing equipment have been developed over the past twenty years. The most commonly applied shear test is that based on a translatory shear strain. This apparatus, however, has some definite limitation in its restricted strain distance, requiring a new sample to be prepared for each test. Hoppe and von Eisenhart Rothe [2] describe the shear testing technique used so far and discuss the rotational shear tester

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Prof. Dr. W. Dreyer, Dept. of Mining, Technical University Clausthal, D-3392 Clausthal-Zellerfeld, Fed. Rep. of Germany

in greater detail. With the automatic programmer, all tests are conducted under similar conditions, eliminating possible operator errors.

3. Bunker Design

The shape and size of the bunker outlet greatly influences the flow pattern of the bulk material. Experiments on flow and pressure behaviour of the stored materials in relation to the shape of bunkers were made by Reisner.

A review of various bunker installations and special bunker shapes, utilised in the storage of bulk materials which have difficult flowability characteristics is given by Reisner [13]. Discharge aids and discharge equipment for the emptying of bunkers are also mentioned, and reference is made to the various types of equipment currently utilised for measuring the charge level.

In tests with a flat-bottom central outlet bin model, the movement of layers was uniquely followed on film. According to Reisner [17] there is an irregular flow referred to as core flow — providing the diameter of the outlet is small. The larger the outlet becomes, the better the flow conditions that prevail, and hence a more regular motion is observed in the whole bin, approaching mass flow, which is of course the preferred type of flow. It is possible to discharge bulk materials from bins by suitable constructive measures at the bin bottom, even without the aid of mechanical discharging devices. Correct material choice and design of hopper surfaces is particularly important; they must be smooth and steep enough to effect massflow. In rectangular and square bins the hopper surfaces must be arranged in such a way that they always intersect with vertical wall surfaces. The best flow-promoting measure is the loosening of the bulk material in the lower region of the silo bin.

4. Segregation Phenomena

Where the material to be stored consists of particles varying greatly in size it is a common experience to find that segregation or size separation occurs, which may prove to be a very undesirable feature. Basic knowledge relating to the bunkering of bulk materials has been published by H. Wöhlbier and Reisner [26].

Research on the segregation of bead fillings in model bunkers and their applicability to industrial conditions using the similarity theorem are pointed out by Matthée [9]. After describing the segregation processes on the basis of mathematical interrelationships and after giving the definition of a characteristic value with which to express the segregation, the paper explains the possible application of the similarity theorem to an industrial processing problem such as the bunkering of beads in bulk, with particular reference to segregation. A law to express the amount of segregation in non-dimensionalized form is formulated on the basis of dimensional analysis. Organisation, execution and evaluation of the experiments are discussed and results are given [9].

Segregation has been studied as a part of the complex behaviour of bulk materials. Qualitative observations are reported and the effects that will have to be dealt with in theoretical treatment are described. Methods of representing segregation and of explaining the effects of segregation by physical laws are emphasized by Matthée [10]. The experimental part of the paper deals with the effect of variables on the rate and degree of segregation in geometrically reduced model bins. The scale-up of these results to storage systems of an industrial size is also discussed. As shown by von Eisenhardt Rothe [21] the amount of segregation for one bunker fill and discharge operation, commonly determined by the standard deviation, is not a constant for an existing bunker plant but depends on the different filling situations of the bunker. Hence, it can be shown that measures to improve the homogeneity of discharged material can lead to the opposite effect of an increased degree of segregation if the bin is not properly designed. In this connection not only is the standard deviation to be considered but also the maximum deviation from the desired mixture composition. It is also provable that using the core flow effect of a bunker the amount of segregation can be reduced to a minimum.

Provided the state of segregation of the stored material column is known, the points of filling and discharging the bunker can be properly located. This fundamental result has been successfully applied to an industrial bunker plant and leads to a new concept of blending bulk materials [19] with regard to *in-bin blending*. Reisner and von Eisenhart Rothe [19] describe the phenomenon of size-segregation. In most industrial plants it is important that stored bulk materials do not segregate when they are charged into or discharged from the bin as material degradation during handling and storing may cause additional problems. These phenomena should be eliminated as much as possible, as the change of the particle size and size distribution within the bin may considerably influence the efficiency of operation of downstream processes. The prevention of wear or abrasion of the inside hopper wall is also an important design factor.

An analysis of the segregation problem of particles in the storage of materials has been carried out by von Eisenhart Rothe [25]. Segregation is caused by a series of physical processes during filling and discharging the hopper. Basically one must differentiate between phenomena at the surface and in the bed of the bulk material. In both cases different mobilities of individual components can exist, as detailed by Kahl and von Eisenhart Rothe [5]. In the handling of bulk materials, segregation is very often an expensive and disturbing secondary matter. To avoid a change in grain size distribution during discharge mass flow, the installation of inserts or the excentric location of the bunker outlet were found to be an improvement in every case comparing the conditions for conventional core flow bunkers with central filling and discharge [5]. By taking the standard deviation as a segregation index for one bunker fill and discharge operation this could be verified quantitatively. In one fundamental study tests were run to model such proposals for improving the blending quality of discharged bulk materials.

A storage plant has the function of equalizing discontinous and continuous conveying systems. That implies that all filling levels between *bin full* and *bin empty* are possible if the assumption is made that the storage capacity is optimized and not overdesigned. Therefore, the question is whether the amount of segregation in the bin might be described by a single criterion or whether the amount or extent of segregation will be changed with different stored quantities of material (Fig. 1).

Fig. 1 shows a typical situation for *core flow* pattern with central filling and discharge. As the criterion for segregation the standard deviation as well as the segregation index E will be considered (Fig. 2).

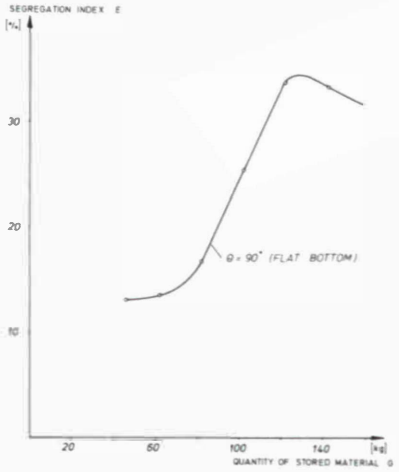

Fig. 1: Segregation characteristics for a core flow bin with central filling and discharge

As detailed in Fig. 2 the pattern and degree of segregation is dependent upon the corresponding quantity of stored material. When the bunker was filled up to 75% [5] a standard deviation σ of 4.6% was found by analysing the deviations of grain size distribution during discharge. On filling the bunker to 22% [5] of its storage capacity a higher value of 8.9% for the standard deviation was observed (Fig. 3).

To compare the quality of blending between mass and core flow, the segregation characteristics for three different hopper angles were considered as detailed in Fig. 3. The correspondent flow profiles can be characterized as core flow, mass flow in stream tubes and mass flow with regular lowering the material level down to the hopper transition (Fig. 4).

The stored bulk material was analyzed by dividing the total volume into concentric sections. Since the conditions for segregation were the same for every filling height, the state of segregation could be demonstrated by the grain size distribution of the bunker cross-section (Fig. 4). In this case most of the fines were concentrated excentrically within a distance equal to 0.7 of the bin radius. On the other side of the bin centre, material was found to be in a relatively by good state of mixing (Fig. 5).

The segregation indices in Fig. 5 represent a constant filling degree of the model bin. By inserting discs with different diameters concentrically within the bin, the highest degree of segregation did not in actual fact result from the central discharge but from an insert which covered 20% of the bunker cross-section. The lowest segregation index *E* was determined for the insert covering 60% of the bunker cross-section. By installing concentric discharge slots in the flat bottom of the bin, the

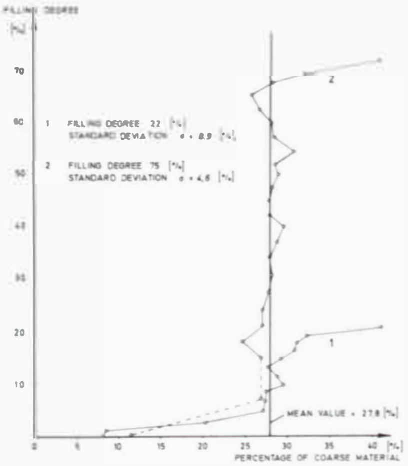

Fig. 2: Deviations in mixture during filling

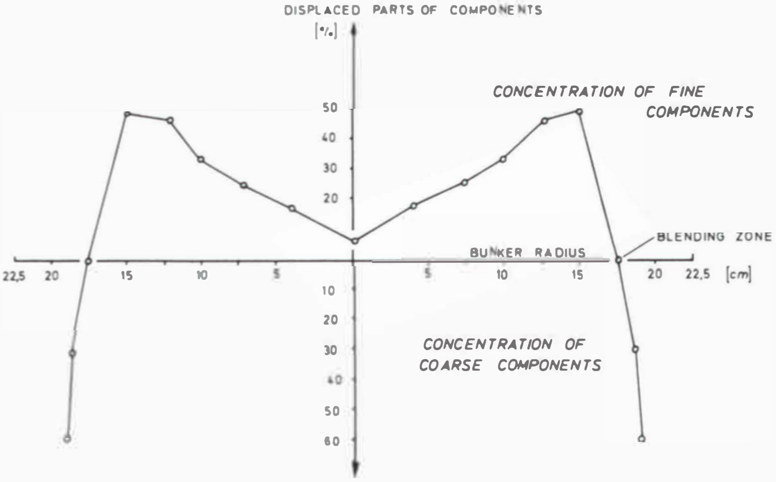

Fig. 4: Grain size distribution in the bunker cross-section

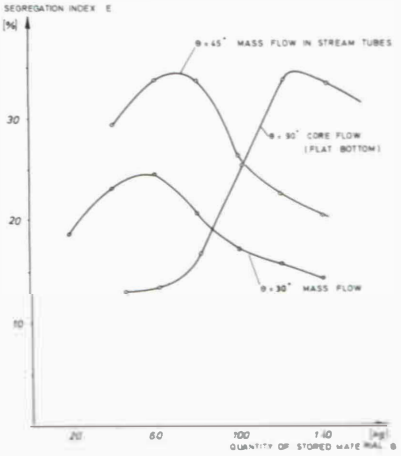

Fig. 3: Segregation characteristics for mass and core flow patterns — central filling and discharge

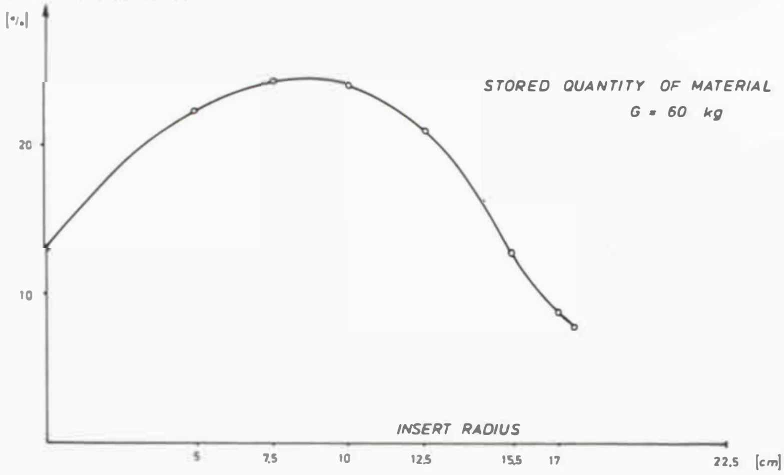

Fig. 5: Segregation indices for various flow-zone placements

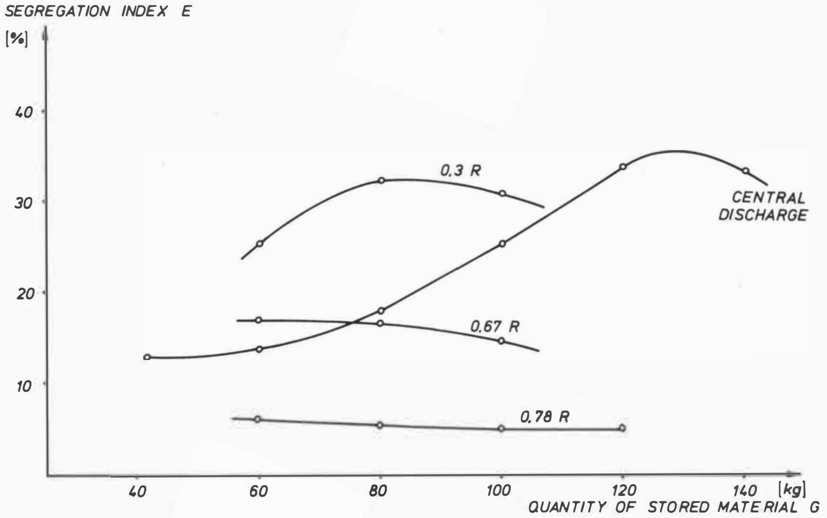

Fig. 6: Segregation characteristics for various flow zone positions

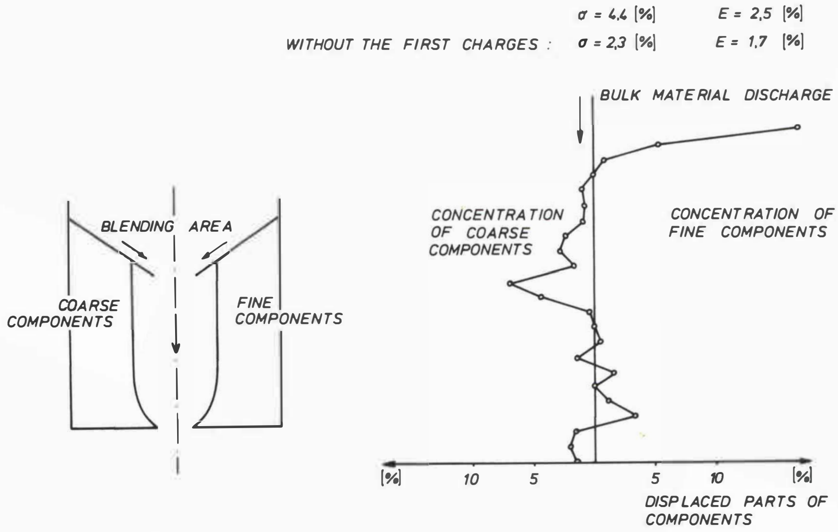

Fig. 7: In-bin blending in a core flow bin

position of the flow zone could be varied (Fig. 6).

For four significant positions the corresponding segregation characteristics are as shown in Fig. 6. Minimum segregation can be achieved if the flowing zone is identical with the blending area (Fig. 7).

The concept of a blending area in a core flow bin leads to the idea of using the core flow pattern for blending different bulk materials. Similar to the method of in-bin blending the components are inloaded separately. In a model test the bunker was divided into two compartments by a plate which was withdrawn after both compartments were completely filled. As shown in Fig. 7 the discharged material was fairly well blended with a segregation index of only 2.5 % and a standard deviation of 4.4 %. Only the first charge was segregated to 16 % and the stationary phase of the core flow bin was not reached. Excluding the first charges in the calculation the blending parameters improved 1.7 % for the segregation index E and 2.3 % for the standard deviation. Comparing the *in-bin blending* method by mass flow, the advantage of this method is that the blending is realized by one filling and discharge cycle. Blending can be performed in either a batch mode or in a continuous manner.

5. Load Calculations and Measurements

The definition of mass flow states that "the movement of bulk materials takes place along the wall of the bunker over the whole height of the bin." For *mass flow* bunkers standard design formulas to calculate the silo loads are given by Reisner [14]. With a horizontal bottom to the bunker, the specific pressure acting on the outlet increases in logarithmic progression as the bulk material weight increases. Pressure increases rapidly as the ratio of bunker base area to opening area increases. In this connection the pressure absorption phenomenon in the bulk material was investigated. With a conical bunker bottom, an angle of about 25° results in minimum pressure and for this reason bunkers should be designed in the optimum range where the lowest bottom pressure can be combined with a comparatively high mean weight flow and the smaller the outlet, the greater is the influence of the water content of the bunkered bulk material on the subsequent decreasing mean weight flow.

After critical considerations of the pressure theory, calculations were conducted concerning the pressure distribution in the bunkers and silos. The first and perhaps most important step in the structural design of a bunker is the determination of the vertical and lateral pressure operative under static conditions. The vertical pressure σ_v in the cylindrical section set up after filling the bunker is given by:

$$0 \leqq z \leqq h_1$$

$$\sigma_v = \frac{\gamma d_1}{4 \lambda \operatorname{tg} \beta} \left[1 - e^{-\frac{4 \lambda \operatorname{tg} \beta}{d_1} z} \right] \qquad (1)$$

Where the side pressure is:

$$\lambda = 1 - \sin \delta \qquad (2)$$

and where:

z = depth of point of interest in the bunker
h_1 = height of the cylindrical upper part of the bunker
γ = specific weight of the grain material
d_1 = diameter of the cylindrical section of the bunker
β = angle of sliding friction between the bulk material and the bunker wall
λ = side pressure coefficient
δ = angle of internal friction

Considering the model bunker installations utilised by von Eisenhart Rothe and Natau [22] which were filled with spherical grains holding an angle of internal friction of 26.10° and hence, giving via equation (2) a side pressure coefficient of 0.56.

The remaining model parameters and specifications are as follows:

$h_1 = 1.00$ m, $d_1 = 0.448$ m,
$\gamma = 6.3$ kPa/m, $\beta = 18.53°$

Utilising equation (1) yields:

$$0 \leqq z \leqq 1\,\text{m}$$

$$\sigma_v = 3.7592\left[1 - e^{-1.676\,z}\right]\,\text{kPa} \qquad (3)$$

At the bottom of the cylindrical section, that is, at $z = 1$ m, the ground pressure was:

$$P_1 = 3.056\,\text{kPa}$$

In the region of the conical section the following relationship was found to hold:

$$h_1 \leqq z \leqq h_2$$

$$\sigma_v = \gamma\,\frac{E - z}{D - 1}\left(p_1 - \gamma\,\frac{E - h_1}{D - 1}\right)\cdot\left(\frac{E - z}{E - h_1}\right)^D \qquad (4)$$

whereby

$$E = \frac{d_1}{d_1 - d_2}\,h_2 + h_1 \qquad (5)$$

and

$$D = 2\lambda\,\frac{\text{tg}\,(\alpha + \beta)}{\text{tg}\,\alpha} \qquad (6)$$

$$\alpha = \text{arctg}\,\frac{d_1 - d_2}{2\,h_2} \qquad (7)$$

Noting that $d_2 = 0.108$ m and $h_2 = 0.40$ m and utilising equation (7), the hopper angle was found to be:

$$\alpha = 23.03°$$

Utilising equation (6) this leads to the value of the constant D

$$D = 2.3365$$

and from equation (5)

$$E = 1.5271\,\text{m}$$

Hence equation (4) reduces to:

$$1\,\text{m} \leqq z \leqq 1.4\,\text{m}$$

$$\sigma_v = 7.1983 - 4.7137\,z + 2.5512\,(1.5271 - z)^{2.3365}\,\text{kPa} \qquad (8)$$

At the bottom of the cone section ($z = 1.4$ m) the ground pressure was:

$$P_2 = 0.6197\,\text{kPa}$$

The height of the cylindrical section of the hopper outlet h_3 was equal to 0.60 m.

In this section of the hopper the vertical pressure was found via equation (9) below:

$$h_2 \leqq z \leqq h_3$$

$$\sigma_v = \frac{\gamma\,d_2}{4\lambda\,\text{tg}\,\beta} - \left(\frac{\gamma\,d_2}{4\lambda\,\text{tg}\,\beta} - P_2\right)\cdot e^{-\frac{4\lambda\,\text{tg}\,\beta}{d_2}(z - h_1 - h_2)} \qquad (9)$$

Hence:

$$1.4\,\text{m} \leqq z \leqq 2\,\text{m} \qquad (10)$$

$$\sigma_v = 0.9062 - 0.2865\,e^{-4.1481(z - 1.4)}\,\text{kPa}$$

At the closed outlet ($z = 2$ m) the static pressure was $P_1 = 0.8824$ kPa. However, it was shown [23] that pressures during the flow of granular materials from bunkers can be much greater than the static pressures, as is shown by von Eisenhart Rothe and Natau [23].

In the conical section of the bunker, however, the lateral pressure ratio is equivalent to the active pressure coefficient:

$$\lambda = \frac{1 + \sin\delta}{1 - \sin\delta} \qquad (11)$$

The measured side pressure coefficient

$$\lambda = 2.40 \quad \text{(measured)}$$

is in good agreement with the theoretical prediction

$$\lambda = 2.56 \quad \text{(predicted)}$$

and indicates arch-like stresses. An extensive outline of the vertical and horizontal stress distribution and typical experimental results for various depths down the bunker axis for different bunker shapes and a selection of h/d ratios is presented by Hoppe [3].

The type of flow observed relating to particular bunker shapes, the reproducibility of results and the effect of the size of the pressure-sampling device are considered. Recent codes of practice have recognised that overpressures should be taken into account in the bunker design. These recommendations are based on the experimental determination of the pressures set up during discharge.

Full understanding of the mechanism of overpressure is, however, not yet complete, theories vary from the breakdown of local arching patterns to acoustic shock wave effects.

Investigations at the Technical University Clausthal into the flow patterns of granular materials in bunkers and silos suggest that overpressures are not transient but are a steady state phenomenon resulting from the existence of fundamental flow patterns.

6. Determination of Discharge Quantities

After a critical analysis of the existing equations for determining quantities discharged from bunkers per unit time, a pattern which can be used in conjunction with specific equations was developed [8].

A process for improving the flow behaviour of bunkered bulk materials is described, in addition to the influence of the laws of soil mechanics and the scope and limitations of its use [8].

Reisner and von Eisenhart Rothe [20] have pointed out that the type and size of feeder for a given application is primarily dictated by the customers' specifications of capacity and the characteristics of the material to be handled. Cost and power comparisons have been given and it was pointed out which material particle sizes are compatible with which type of feeder. The capacities, advantages, disadvantages and limitations of various feeders were detailed [8].

For a particular installation feeders are to be evaluated by considering cost, maintenance requirements, space limitations for the feeder, control requirements for the process, the accuracy of the flow regulation and the uniformity of flow plus many other factors.

For effective operation, bunkers must permit the stored material to discharge by gravity flow. The particular aspects of the flow and discharge of salt in large bunkers was dealt with by Lotze and Hoppe [7]. The application of certain observations detailed in connection with the design of new bunkers and for the improvement of the working characteristics of existing bunkers are given [7].

A steep bunker layout takes place through a slot shaped core within which groups of material particles slide downward rapidly towards the oulet. Strips of material slide down the inclined regular free top face into the core. The flow pattern is irregular, being first from one side of the bunker and then from the other; also within the core the moving groups of particles continually break up and reassemble. The results of further experiments are detailed which throw further light on to the particular properties of the flow characteristics of salt from bunkers and offer a simple method of controlling the outflow.

7. In-Bin Blending and the Use of Flow-Corrective Inserts in Bins

In order to achieve constant input conditions for production processes, it is very often necessary to compensate for the deviations in the quality of the material stream or to blend different materials with each other in order to retain a mixture within a narrow range. As shown by H. Wöhlbier, von Eisenhart Rothe and Kahl [29], it is possible to achieve sufficient homogenization in a bunker providing the equipment for charging and discharging is specifically designed for this purpose. Feeders are used to provide a means of control for the withdrawal of bulk materials from storage units. This control function can only be performed properly as long as the bulk materials flow by gravity to the feeder in a uniform and uninterrupted fashion. Feeders must be considered as an integral part of the overall bin and feeder system. Efforts have been made to determine the load or pressure on feeders mounted directly underneath the hopper opening. Recent studies have shown that greatly reduced pressures occur at the bottom of hoppers because of the converging configurations of the hopper walls.

Many existing installations for storing particular solids include hoppers from which funnel flow takes place, and although it is desirable to replace them by mass flow hoppers this may not be economic. It is possible to convert the hopper into a mass flow hopper, or to reduce the tendency to form stable arches or pipes by the use of a conical insert. A method is given for the design of the insert, and methods for estimating the pressure on the insert are treated by Kahl [4]. As a result, the total vertical force on the insert may exceed the weight of the solid directly above the insert. The loading of inserts in bins depends on the properties of the bulk material stored in the bin, the bin size and shape, as well as the insert size and position in the bin.

Kahl and Hoppe [6] show that the maximum vertical force exerted on the insert in a bin can be calculated. This force exists on the insert only under initial loading conditions and the force during steady flow from the bin is much less, therefore the insert should be supported with sufficient structural members.

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