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The Use of Measured Flow Properties for Dimensioning the Outlet of a Mammoth Silo for Coal Storage

G. Haaker, The Netherlands

Summary

This article describes a procedure for predicting the outlet size of a large flat-bottomed coal silo to ensure reliable flow. The design is based on the flow properties measured on relevant samples of the bulk solid and a mixture of existing silo theories and common sense. Due to the special features of the Eurosilo not all the steps in the procedure are actually needed in the case described, but are given for completeness.

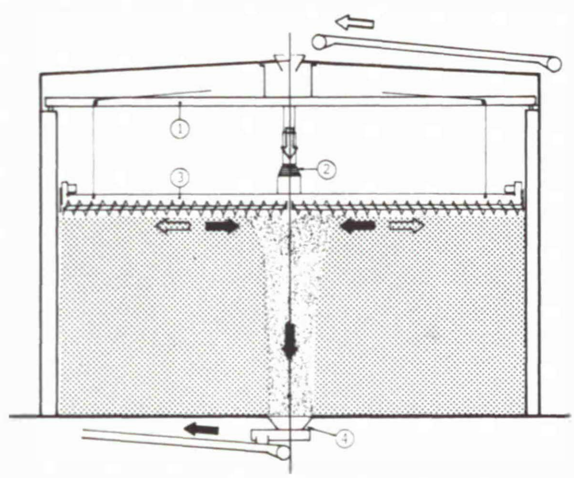
Nomenclature

A	Cross-sectional area of flow channel	m²
b_{min}	Minimum diameter to prevent arching	m
D	Diameter of silo	m
d_{cr}	Critical diameter to prevent piping	m
ff_c	Flow function of bulk solid	—
ff_{ct}	Time flow function	—
ff_p	Flow factor for no-piping	—
H	Maximum filling height of silo	m
o	Cross-sectional perimeter of flow channel	m
ϕ_e	Effective internal friction angle	o
ϕ_t	Static internal friction angle	o
ϕ_w	Wall friction angle	o
λ	Principle stress ratio	—
ϱ	Bulk density	kN/m³
σ'	Main principle stress at dome or pipewall	kPa
σ_c	Consolidating pressure	kPa
σ_p	Unconfined yield strength	kPa

1. Introduction

At the end of 1980 work commenced on the design and construction of a mammoth silo of the Eurosilo type [1], for the storage of approximately 10,000 metric tons of coal. This type of silo is basically a cylindrical-shaped, covered ground storage for large amounts (up to 100,000 m³) of bulk solids. A typical cross-section is given in Fig.1.

The bulk material is loaded through the top centre of the silo, using a telescopic chute to avoid the formation of dust. A suspended feeder/conveyor system distributes the material



⇨ Direction of flow - filling

➡ Direction of flow - discharging

Bulkmaterial at rest

Bulkmaterial in downward flow

(1) Rotating bridge structure

(2) Telescopic filling tube

(3) Distributing screw conveyor

(4) Emptying mechanism

Fig. 1: Cross-section of the original Eurosilo concept

over the top surface. On emptying this same system directs the material back to a central flow channel formed within the material, where it is withdrawn by gravity flow through the outlet in the bottom centre of the silo. The features of this Eurosilo storage system are described elsewhere [2].

With the foundations of the silo already under construction, little was known about the required outlet geometry. The existing outlet design had been based on some practical experience of the manufacturer of the vibratory feeder to be installed under the outlet.

It was then decided that a more fundamental review of this aspect was required, based on the properties of the material

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to be stored and an application of existing silo theories. This article gives a stepwise review of the design process.

2. Material and Measurement

Several coal types were expected to be stored in the silo, so the coal with the worst flow properties (known from experience) was selected as the reference material. A 25 kg sample of this coal was taken for the laboratory testing, and all the particles above 5 mm were sieved out to suit the requirements of the testing apparatus. All tests were performed in the powder-laboratory of the Twente University.

Three instantaneous yield loci were measured with a Jenike shear tester [3], with each point being measured twice and a fresh sample taken for every test.

From several test samples the moisture content (average of 8 %) and the bulk density, ϱ, were established.

From the yield loci the relevant flow properties were derived, i.e., the effective internal friction angle ϕ_e and the unconfined yield strength σ_p, both as a function of the consolidating stress σ_c. In Fig. 2 these derived results are shown, together with the measured density values.

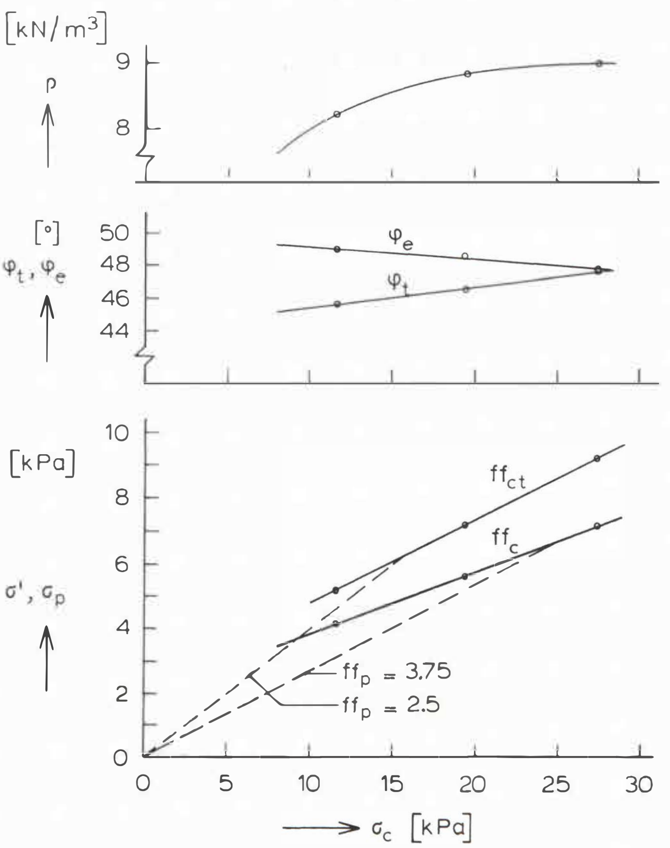

Fig. 2: Measured flow properties of coal

To approximate the influence of a period of undisturbed storage on the flow properties, four tests were performed with 24 hours time consolidation. These tests all showed an increase of about 17 % in the shear stress due to time consolidation. To reduce the quantity of testing it was decided to apply this percentage to all points of the yield loci to get a fair estimate of the time yield loci. The time flow function derived from these yield loci is given in Fig. 2 as ff_{ct}.

3. Application of the Flow Properties

3.1 Upper Bound of the Critical Piping Diameter

As this flat-bottomed silo is of the Funnel flow type, the critical outlet dimension to avoid the formation of a stable pipe within the material must be calculated.

The material forming such a pipe gains its strength by the consolidating pressure σ_c of the material above. Because of the low height to diameter ratio of the silo (H = 17.2 m, D = 29 m) this consolidating vertical pressure can be assumed to be linear with depth. This leads, with a value of ϱ = 9.25 kN/m³ chosen from Fig. 2, to a consolidating pressure at the bottom of the silo of

$$\sigma_c = \varrho \cdot H = 9.25 \times 17.2 \simeq 159 \text{ kPa}$$

The accompanying value of the unconfined yield strength σ_p can be established by linear extrapolation of the flow function, approximated by

$\sigma_p = 2 + 0.19\, \sigma_c$, which yields:

$$\sigma_p = 2 + 0.19 \times 159 \simeq 32.2 \text{ kPa}$$

The critical piping diameter, d_{cr}, can be calculated from:

$$d_{cr} = \frac{\sigma'_{cr} \cdot G(\phi_t)}{\varrho}$$

in which σ' represents the major stress applied at the surface of the pipe, and in the critical case must be equal to σ_p. The angle ϕ_t is called the static angle of internal friction of the material, while the function $G(\phi_t)$ is calculated by Jenike and given in [3] and [4]. For the considered coal $\phi_t \simeq$ 46° was derived from the yield loci, which yields $G(\phi_t)$ = 4.3, leading to:

$$d_{cr} = \frac{32.2 \times 4.3}{9.25} \simeq 15 \text{ m}$$

Obviously such a value for the outlet, to avoid a stable pipe in the silo, is rather unrealistic in practice, and if the influence of time consolidation was taken into account, this value would even be larger. One can, however, argue that the linear extrapolation of the flow function probably exaggerates the value for σ_p, but this can not be checked as the shear tester is not suited for this high pressure range. But even if the value found for the piping diameter can be decreased by say 30 %, it still will not lead to a useful practical solution.

3.2 Lower Bound for the Critical Piping Diameter

To increase the silo activity the design incorporated horizontal srew conveyors to transport the material to the centre of the silo. This means that the formation of a stable pipe does not conflict with the desired action of the silo.

As a start in calculating a more attractive outlet size, the critical piping dimension can be determined by an earlier approach [3, 4]. Here the influence of the surcharge of the material upon the consolidation of the pipewall is neglected.

Taking ϕ_e = 49°, ϕ_t = 46°, which gives $G(\phi_t)$ = 4.3, the flow factor for no piping can be calculated as:

$$ff_p = \frac{\sigma_c}{\sigma'} = \frac{1 + \sin \phi_e}{4 \sin \phi_e} G(\phi_t) \simeq 2.5$$

The intersection of $ff_p = 2.5$ with the instantaneous flow-function in Fig. 2 yields

$$\sigma'_{cr} = \sigma_p = 3.7\ \text{kPa}, \qquad \varrho = 8\ \text{kN/m}^3$$

leading to a critical piping diameter:

$$d_{cr} = \frac{\sigma'_{cr} \cdot G(\phi_t)}{\varrho} = \frac{3.7 \times 4.3}{8} \simeq 2\ \text{m}$$

3.2.1 Correction to the lower bound value

The lower bound value of d_{cr} requires two corrections:

a) The first takes into account a negative influence from the vibrating hopper, leading to a consolidation of the material. This can be achieved by applying a safety factor of 1.5 to the flow factor, as suggested by Arnold et al. [4] in the case of no-doming flow factors.

The intersection of this corrected $ff_p = 3.75$ with the flow function in Fig. 2 gives:

$$\sigma'_{cr} = \sigma_p = 6.4\ \text{kPa}, \qquad \varrho = \simeq 9\ \text{kN/m}^3$$

$$d_{cr} = \frac{6.4 \times 4.3}{9} \simeq 3\ \text{m}$$

b) The second correction takes into account the time consolidation during storage at rest.

In this case the time flow function ff_{ct} is used and from the intersection with $ff_p = 2.5$ in Fig. 2 it follows:

$$\sigma'_{cr} = \sigma_p = 5.8\ \text{kPa}, \qquad \varrho = 8.5\ \text{kN/m}^3$$

$$d_{cr} = \frac{5.8 \times 4.3}{8.5} \simeq 2.9\ \text{m}$$

From the calculations so far, an outlet of about 3 m is seen to be satisfactory, as far as no worse conditions prevail in the silo. It must, however, be noted that the lower bound approach in most cases seriously under-estimates the values of d_{cr} and is only valid when the silo is discharged during filling. As this is not the normal practice in the operation of the silo, it is likely that a stable pipe of about 3 m diameter will form within the material.

In view of the operation of the reclaim screw conveyors in the silo, this does not present any difficulty in our case. However, one has to ensure that a stable dome cannot form in such a pipe, requiring that the diameter of the outlet must be analysed in that respect.

3.3 Minimum Outlet Dimension to Prevent Arching

Arching must be considered under the following conditions:

a) When the material forming the arch is consolidated by the full hydrostatic pressure acting on the material.

This will be the situation when the silo is completely filled without any discharge of material during filling. In this case, as already calculated in 3.1,

$$\sigma_c = 159\ \text{kPa}, \qquad \sigma_p = \sigma'_{cr} = 32\ \text{kPa}$$

and the critical dimension can be calculated with

$$H(\alpha) \simeq H(0) = 2, \qquad \varrho = 9.25\ \text{kN/m}^3, \text{ which gives:}$$

$$d_{min} = \frac{\sigma'_{cr}\, H(\alpha)}{\varrho} = \frac{32 \times 2}{9.25} \simeq 6.9\ \text{m}$$

Because $d_{min} = 6.9$ m exceeds the chosen outlet size of 3 m, it is obvious that a stable arch can form over the outlet in this situation. This can be avoided by discharging some of the material during filling, so that flow conditions prevail in the flow channel with less consolidating stress upon the material.

b) In normal use, when a flow channel is formed within the material. Now the situation is as given in Fig. 3.

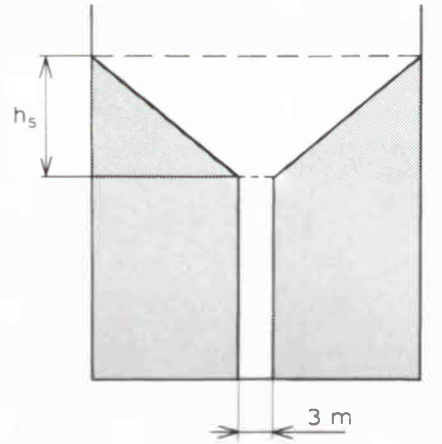

Fig. 3: The flow situation in normal use

First the depth, h_s, at which a stable channel can start to form in the material must be calculated. This can be done by inversion of the upper bound approach of 3.1, with

$$\phi_t = 46°, G(\phi_t) = 4.3, d = 3.0\ \text{m}, \varrho = 8.0\ \text{kN/m}^3$$

which leads to:

$$\sigma' = \frac{d \cdot \varrho}{G(\phi_t)} = \frac{3.0 \times 8.0}{4.3} = 5.6\ \text{kPa}$$

This stress on the pipewall must in the critical case again equal the unconfined yield strength σ_p of the material. From the flow function in Fig. 2 the accompanying consolidating pressure σ_c can be derived, which in this case can be regarded as linear with depth, leading to a value of h_s:

$$\sigma' = \sigma_p = 2 + 0.19\,\sigma_c = 5.6\ \text{kPa}$$

$$\sigma_c = \frac{3.6}{0.19} = 19 = \varrho \cdot h_s \rightarrow h_s \simeq 2.4\ \text{m}$$

So from a depth of about 2.4 m, a stable pipe of 3 m diameter can be expected in the material. For this situation the consolidating pressure at the bottom of the channel can be approximated according to Janssen's theory, with a surcharge from the material above the channel.

This leads with $\phi_e = 49°$, $\phi_w = \phi_e$ to:

$$\sigma_c = \sigma_v = \frac{\varrho \cdot A}{\lambda \cdot o \cdot tg\,\phi_w} = \frac{9x3}{0.14x4x1.15} \simeq 42\,kPa$$

Thus $\sigma_p = 2 + 0.19\,\sigma_c \simeq 10\,kPa$, and the critical diameter for a stable bridge to occur follows with $\sigma'_{cr} = \sigma_p$ from:

$$b_{min} = \frac{\sigma'_{cr} H(\alpha)}{\varrho} = \frac{10x2}{9.25} \simeq 2.2\,m$$

As $b_{min} < 3$ m a stable bridge will not form over the outlet. For the 24 hour time consolidation the time flow function gives an increase of σ_p of about 30 %, leading to $b_{min} = 2.7$ m < 3 m. Thus a stable arch will not occur even after 24 hours of undisturbed consolidation.

4. Some Remarks on the Solution

The lower bound approach for the critical piping diameter was used as a starting point to define a more practical opening diameter. From the calculations shown it can be seen that a value of 3 m is near the optimal solution. Similar calculations on selected values for the opening of 2 and 2.5 m indeed indicate that stable arches over the outlet are likely in these cases.

Thus an opening of 3 m diameter was chosen, taking into account a disturbance of the material during a complete filling. As already discussed, time consolidation is only considered over a 24 hour period, in accordance with the expected undisturbed time storage in practice. If a longer storage period is necessary, it will be useful to discharge small amounts of material at regular intervals.

The final silo design, of which Figs. 4 and 5 give some impressions, was commissioned about one year ago and has performed satisfactorily to date.

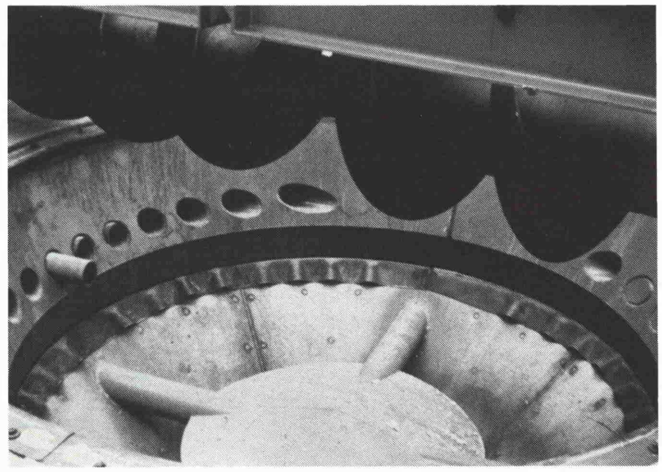

Fig. 4: The actual outlet and the horizontal srew conveyor in the lowered position

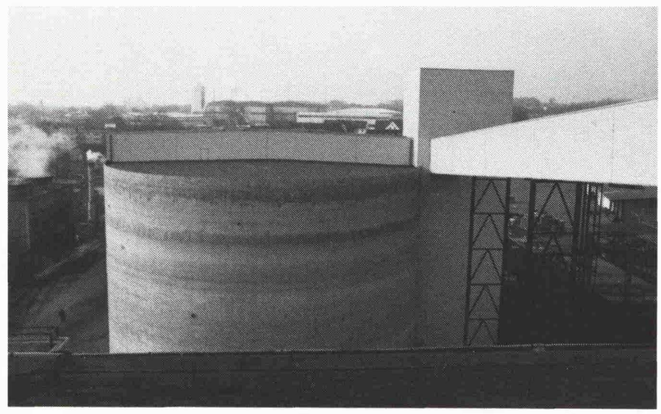

Fig. 5: General view of the Eurosilo used for coal storage

References

[1] Van den Broek, S.E.D., "Recent developments and future trends in large scale storage of bulk solids", 1979, Eurosilo Holland, NL-1520 AA Wormerveer, Holland.

[2] Rademacher, F.J.C., "Advantages of the Eurosilo concept for the covered storage of coal and other non-food commodities", Aufbereitungs-Technik 22 (1981), No. 11, pp. 587—599.

[3] Jenike, A.W., "Storage and flow of solids", Utah Univ. Eng. Exp. Stn., Bull. 123 (1970).

[4] Arnold, P.C., McLean, A.G., Roberts, A.W., "Bulk Solids, Storage, Flow and Handling", Tunra Ltd., University of Newcastle, Australia, 1979.

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