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Silo Problems

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Silo Probleme
Problèmes de silo
Problemas de los silos
サイロに関する諸問題
地下仓问题
المشاكل المرتبطة بالصوامع

Summary

This article tries to prove that silo design is the most difficult of all subjects in the field of civil engineering. The major errors in silo design are discussed and examples are given of silo deformations, fractures and collapses.

1. Introduction

This article is dedicated to Dr. Otto F. Theimer in recognition of his work and publications on the subject of silos. When, in 1971, I read his article "Failures of Reinforced Concrete Grain Silos" [2], I was able to confirm how complex the design and calculation of silos is. At that time I was in charge of the structural calculation of 90 silo installations, of which 30 had suffered serious problems and one had collapsed. Generally, when a silo installation produces problems, the causes are multiple and varied — and it is the total sum of these which results in failure.

Of significance is a comment made by Otto Theimer during his speech at the Meeting on Grain Milling Technology at Detmold, Germany in 1963: "In no other field of advanced constructional engineering are there so many dangers and risks as in the field of silo construction".

In 1978 I published a book dealing solely with problems in silos, which contained 48 specific problems together with more than 165 photographs, all of which I had encountered in twelve years of experience in this complex but exciting field of science.

2. History of Silo Problems

Studies on the design and construction of silos started in 1882 when Roberts made his first tests on a rectangular silo 15 m high in order to calculate pressures. The first mathematical expression of lateral and vertical pressures was obtained by Janssen in 1895. Since then, his formula has been constantly applied, although to date the problems have not ceased. During the nineteen-sixties there began a strong drive to define and calculate the pressures produced by the stored material on the walls and hopper.

The Symposium on Silos held at the University of Lancaster in September 1980 was attended by 148 participants from all over the world. The subject of calculation of pressures in silos was defined, in the case of granular products, with an overpressure coefficient of 2.32 in relation to Janssen's pressures (Platonov's theory, ACI, DIN 1055 — 1980, Ravenet, Theimer). Nevertheless, the storage of cohesive powder products gives rise to enormous problems, with overpressure coefficients exceeding 5. No specialist has come up with a theory for calculating pressures, and the majority of silos built for storing powder products suffer serious problems of deformation, fracture and even collapse in the medium and long term. Parallel to this, there is another problem: the majority of these silos empty badly and stable arches form over the outlets. Outflow occurs through a core or pipe which takes various arbitrary forms inside the cell.

Two American specialists, Jenike and Johanson, designed the mass flow cell and produced the theory of active and passive forces with a wave of overpressures, and obtained an overpressure coefficient of up to 6.5 in relation to Janssen's theory at the point of connection between the bin and hopper.

The works and bibliography studied show serious silo problems in the following countries: Australia, Japan, South Africa, North Africa, Canada, United States, Brazil, Great Britain, Sweden, Germany, France and Spain.

3. Errors in Silo Design

Although there are many causes of problems in silos, we shall review the most important and those which most frequently occur.

3.1 Foundations

It should be borne in mind that the minimum load on the ground is the load produced by the silo when full. It has also been shown that the stored mass in very large silos is subject to compaction, with an increase in total density of up to 12 % (figures obtained by Ravenet and Lumbroso). If to these values we add those due to wind effects on a full silo, the loads can be particularly high.

There is a general tendency to built very slim silos with a height to breadth ratio of over 5. In the case of multicellular silos, eccentric loads appear due to non-uniform filling of the

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cells and wind effects. Special care should be taken in designing metal silos on account of the possibility of the empty silo overturning.

3.2 Discharge Overpressures

One of the most frequent failure problems is the calculation of the overpressure coefficient, taking as a basis Janssen's formula for static pressures. After examining the theories and tests of more than 37 world specialists, it appears that there is an envelope of lateral discharge pressures with a coefficient of 2.32 in relation to Janssen's pressures.

Janssen's formula is:

$$P_h = \frac{\delta \cdot R}{\tan \varphi'} \qquad (1)$$

P_h = horizontal pressure in kg/m²
δ = density of the ensiled material in kg/m³
R = hydraulic radius, equal to the area/perimeter ratio of the straight section in meters
φ' = angle of wall friction of the material

In Equ. (1) we have as variables δ and φ'. According to the value given to these variables we will obtain totally different figures which can lead to serious errors which may cause fracture or collapse of the installation.

Let us take a cylindrical silo 6 m in diameter and 30 m high. Given values of

$$\delta = \text{density} = 700\ \text{kg/m}^3$$
$$\varphi' = \text{angle of wall friction} = 24°$$

the lateral pressure according to Janssen for H = 30 m will be: P_h = 2,347.06 kg/m², and applying the overpressure coefficient of 2.32, we will obtain a maximum pressure of P_h = 5,445.18 kg/m².

With values of

$$\delta = 880\ \text{kg/m}^3$$
$$\varphi' = 18°$$

the lateral pressure according to Janssen for H = 30 m would be P_h = 3,980.23 kg/m², and applying the overpressure coefficient of 2.32, we will obtain a maximum pressure of 9,234.13 kg/m². By applying different values, we have a 70 % increase in final pressure.

At the time of designing a silo it is very important to carry out laboratory tests on the material or materials to be stored and to calculate the density and angle of wall friction, since the existing tables give variations of up to 70 % on applying formulae for calculation of wall pressures.

Another factor not generally considered when designing a silo installation is the height to breadth ratio. Only such specialists as Airy and Safarian have taken this into account.

Tests carried out by Ravenet on transparent models show that if we have a height to breadth ratio of 7 there is mass flow in the upper two-thirds of the cell (Fig. 1), and where the height to breadth ratio is 1.5 (Fig. 2) there is core or funnel flow. Logically the pressures on the walls are not the same in each case, and therefore the design must be different. It is very important that the silo engineer or specialist should know the behaviour of the ensiled products during the emptying process in order to have one more factor on which to base his hypothesis of calculation. It is therefore necessary to perform tests on transparent models and, equally important, to measure the parameters of density and angle of wall friction. If these factors are unknown, failure may occur.

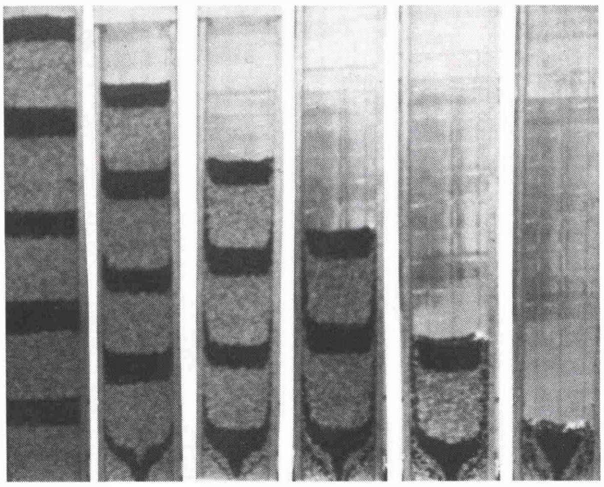


Fig. 1

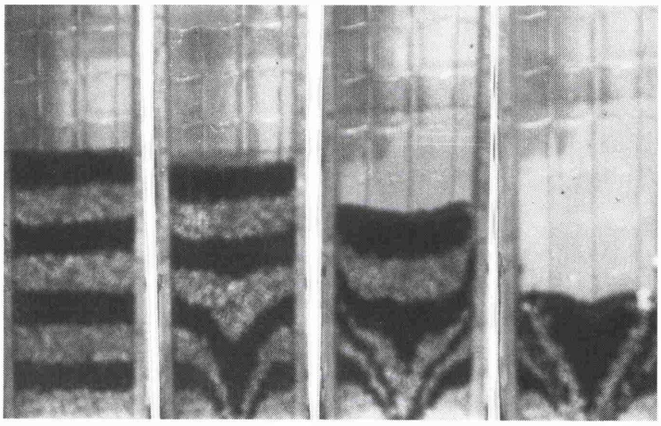


Fig. 2

3.3 Friction Forces

Due to the angle of internal friction and angle of wall friction, compression forces are produced on the walls which may reach 80 % of the weight of the ensiled material especially when the silos are tall. In the case of reinforced concrete silos, these forces are absorbed by the walls, although with very tall silos and high densities the necessary checks should be made. With metal silos, which are generally cylindrical, special care must be taken particularly with regard to friction forces, since these present a new factor, namely bulging of the wall which is generally very thin, but which in part is helped by the ensiled mass itself acting as a rigidifier; the extent to which this bulge can stretch is not altogether known, but has been studied by Weingarten, Morgan and Seide, in tests carried out in Germany which give more conservative values, and by NASA using even higher safety coefficients.

Ravenet has been able to show, in a study of various cylindrical silos which have suffered deformation, that at a given moment the whole ensiled mass is supported on the walls by friction.

The friction forces reach their highest value when discharge commences and particularly when the ensiled material has been static in the silo for several months, forming a cohesive block.

3.4 Pressures on the Silo Bottom

In the case of granular materials, maximum pressure on the bottom is produced during filling, whereas during discharge the formation of unstable arches at various levels produces varying values for lateral and vertical pressures. Tests performed by Pieper, Platonov and Ravenet showed the formation of unstable arches.

In order to calculate pressures on the bottom, value K is applied:

$$K_1 = \frac{P_h}{P_v} = \frac{1 - \sin\phi}{1 + \sin\phi} \qquad (2)$$

where:

K_1 = ratio of horizontal and vertical pressures
P_h = horizontal pressure in kg/m²
P_v = vertical pressure in kg/m²
ϕ = angle of internal friction.

This factor K_1 is based on Coulomb and Rankine's earth thrust theory.

The value of K has also been determined by:

— Yaky: $K_o = 1 - \sin\phi$

— Frazer: $\frac{1}{K} = \frac{1 + \sin^2\phi}{\cos^2\phi} + \frac{2 \cdot \sin\phi}{\cos^2\phi} \cdot \sqrt{1 - \frac{\tan^2\phi'}{\tan^2\phi}}$

— Walker: $K = \frac{1 - \sin^2\phi}{1 + \sin^2\phi}$

The value of K *varies, according to the ensiled material and* the geometric form of the silo, between 0.30 and 0.60.

If the silo walls are rough, pressures on the bottom are low. On the other hand, smooth walls produce high bottom pressures. The formation of unstable arches gives rise to an impact effect, and it is necessary to apply a coefficient ranging between 3 and 7.

3.5 Abnormal Outlets

Up to now we have been referring to granular materials and central outlets. Of the various forms of abnormal outlets, we shall look at:

a) **Eccentric outlets:** For processing purposes and very often for reasons of false economy, eccentric outlets are used in installations for storing granular materials.

In Fig. 3, Ravenet shows emptying sequences in a transparent model with a height to breadth ratio of 6.

In Fig. 4, the test is repeated in a model with a height to breadth ratio of 1.5.

These tests, together with other tests on models measuring lateral pressures with strain gauges, clearly show the enigma of eccentric outlets and the calculation of lateral pressures. (Identical results were obtained by Pieper and Ravenet.) Whenever eccentric outlets are used, lateral pressures are distributed in the following manner:

Side nearest the outlet: A depression appears in the lower part which reaches a value of 0.67 of Janssen's static pressure, and moving upwards the pressure increases to an overpressure coefficient of 1.71.

Side opposite the outlet: There is always an overpressure with a coefficient reaching a maximum value of 1.95.

The non-uniform distribution of lateral pressures in a straight section of a cylindrical silo due to eccentric outlet has produced hundreds of deformations, crackings and collapses in installations all over the world.

Fig. 3

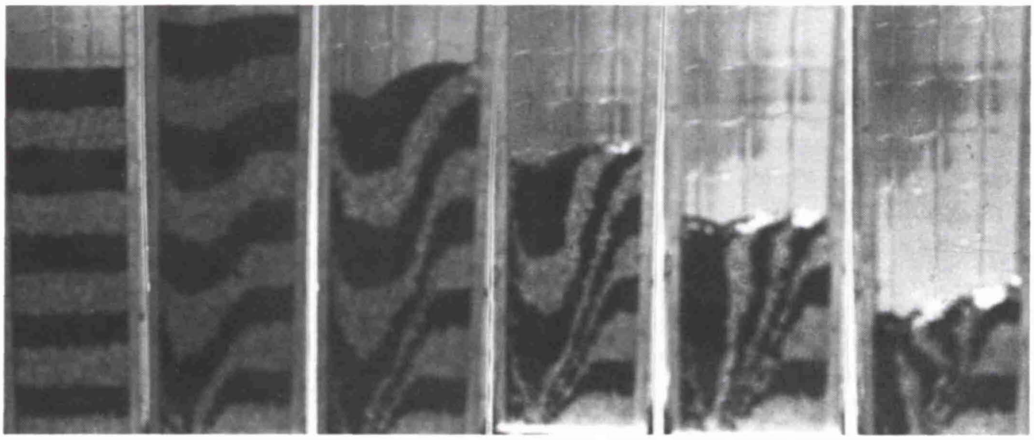
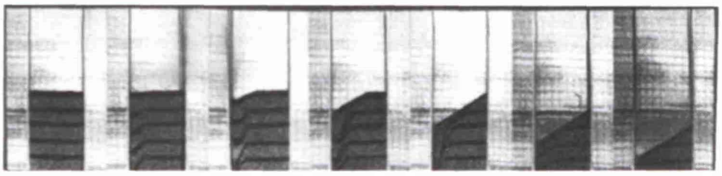


Fig. 4



Even with central outlets there may be a non-uniform distribution of pressures on the walls, as is shown by tests conducted in the U.S.S.R. and described by Leonhardt, Boll and Spiedel which refer to the silos at Amjansk and Octobre.

If the silo is a cylindrical metal one with an eccentric outlet, the lack of transversal rigidity brings about a high degree of ovalisation which puts the installation at risk.

b) **Cells with static flow pipes:** Static flow pipes have a basic purpose which is to produce outflow from the upper part of the cell, as can be seen in the tests on models performed by Ravenet (Fig. 5). The method is certainly original and produces certain advantages initially, such as disciplined outflow of material and absence of overpressures, so that it is possible to apply Janssen's classic formula and achieve a 50% saving in silo costs. Nevertheless, the system is dangerous since, if the flow pipe fails, lateral overpressure phenomena come into play during discharge, and deformation and even fracture of the walls will follow, as can be seen in Fig. 6. Experience over the years has shown that silos with static flow pipes suffer serious structural problems in the long term. The fundamental cause is blocking of the pipe due to impurities or compaction of the ensiled material.

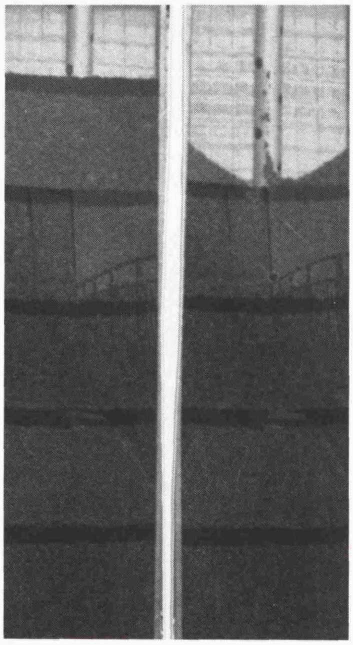


Fig. 5

c) **Multiple outlets:** Another method used in silo design is that of multiple outlets, which give uniform outflow (mass flow) — see Fig. 7. Special care must be taken in the design of the multiple outlets, since an error can lead to eccentric and non-uniform outflow, as shown in Fig. 8.

A test was performed on a model, using strain gauges to measure wall pressures during discharge. The overpressure coefficient turned out to be 1.95.

d) **Pneumatic discharge:** An air jet system is often employed to aid discharge, and this fluidises the material in the area where the compressed air is injected. The small amount of air injected into the cell does not reach the upper part although it does affect a large portion of it. Since the P_a pressure of the air jet is higher than the discharge pressure of the material, the P_a pressure decreases linearly until it reaches a height of h where it coincides with the discharge pressure. The value of h is:

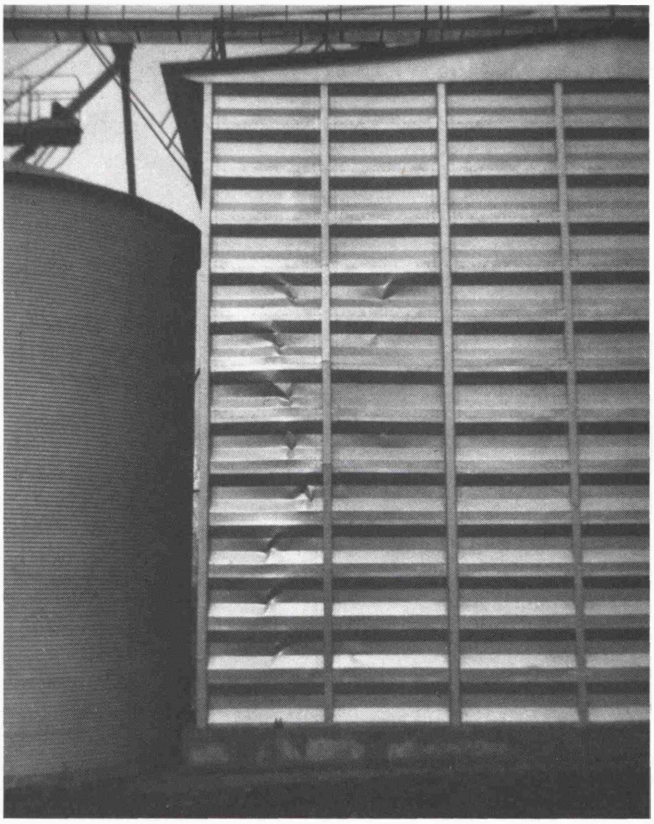


Fig. 6

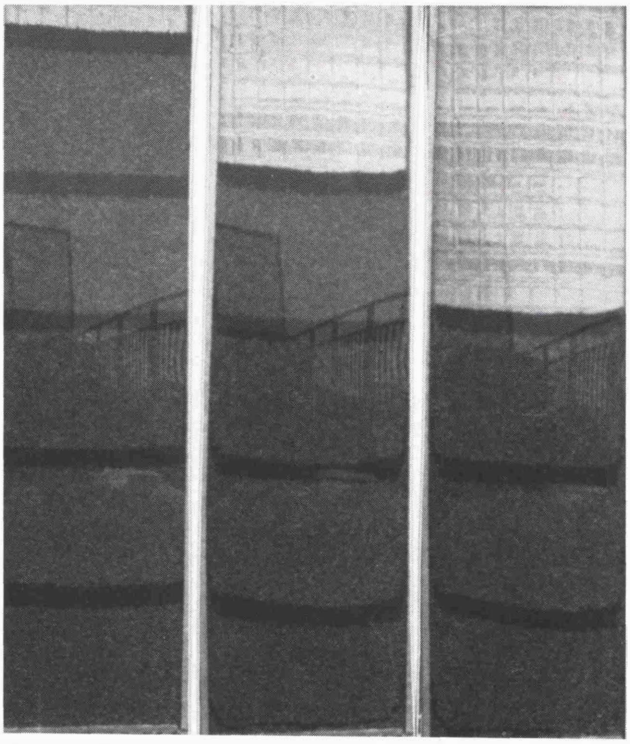


Fig. 7

$$\Delta h = \frac{1.6\,P_a}{\gamma \min} \tag{3}$$

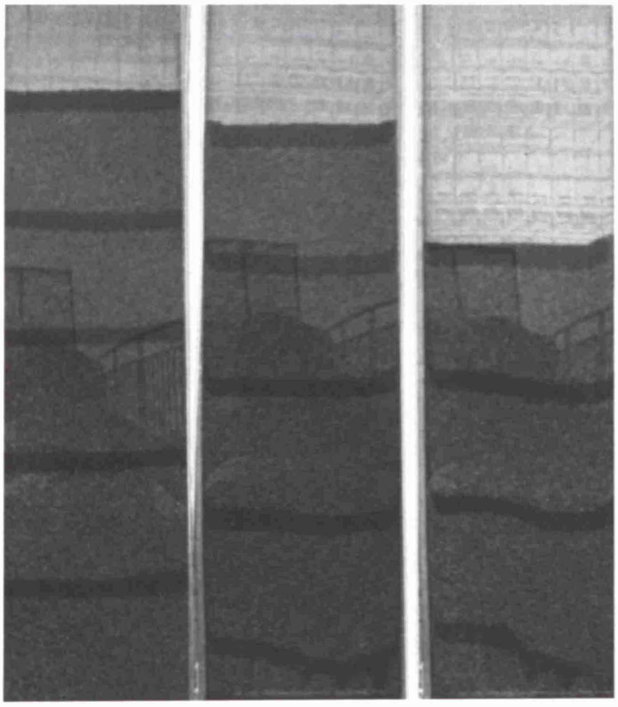


Fig. 8

3.6 Powder Products

The storage of cohesive powder products is one of the most difficult and controversial subjects facing the engineer or estimator. Research has not solved the problems which arise, namely:

a) Formation of arches: Stable arches which normally form over the outlet or on the walls of the hopper must be broken by external vibration or percussion systems.

b) Formation of flow channels: During discharge, cohesion produces central or eccentric channels along which the ensiled mass flows, as can be seen in Fig. 9.

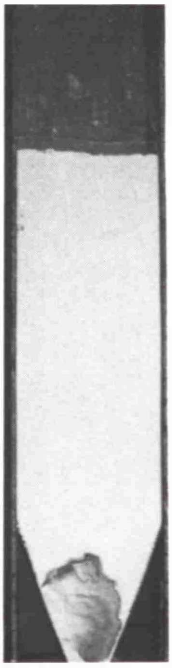


Fig. 9

c) The collapse of arches causes overpressure exceeding 5. These values have been measured with strain gauges in real silos.

The German Standard DIN 1055 (1964), updated in 1977, excludes all cohesive powder products, since installations of this type calculated according to the Standard have exhibited a series of deformation and fracture problems.

3.7 Type of Silo

Of considerable influence on the design of the installation is the type of silo to be used, namely:

a) Unicellular or multicellular.

b) With intercells of diverse geometric form.

c) Reinforced concrete or metal.

Each type of installation requires a specific design treatment once the bases of calculation have been determined. Thus, for example, with reinforced concrete silos special attention must be paid to foundations and cracks that may appear in the walls. If sliding forms are used in construction, the thickness of the wall must be checked to ensure that it accords with the minimum permissible for perfect sliding.

In metal silos, stability against wind effects when empty must be checked; and in unicellular silos, the possibility of ovalisation due to eccentric outlets.

In multicellular silos with intercells, one must ensure that the fixed end moments are absorbed by the walls of the cells, since many problems have arisen in silos on account of this factor.

4. Silo Problems

Having reviewed the errors generally committed in the design and calculation of silos, we shall describe a series of problems that have occurred.

4.1 Foundations

A typical case of insufficient study of the subsoil is that of a multicellular grain (wheat) silo in the province of Lerida (Spain). The silo, measuring 8.46 m total breadth and 30.10 m high, was built on an 0.80 m thick reinforced concrete slab. The total load envisaged on the ground was 1.52 kg/cm². Work started in August 1969, and in January 1970 filling of the installation commenced. When the load transmitted to the ground reached 0.89 kg/cm² there was 20 mm settlement, which increased to 80 mm with a ground load of 0.967 kg/cm². A series of borings showed that at a level of —3.90 there were high plasticity clays which would take a maximum load of only 0.58 kg/cm². This was overcome by drilling shafts to a level of —6.00 where the rockbed was encountered, and laying foundations at this depth.

4.2 Discharge Overpressures

A typical case of fracture due to discharge overpressures occurred in a multicellular reinforced concrete silo with 4 x 4 m square cells and a height of 22 m for storing grain. Fig. 10 shows the state of the silo after the external wall of one cell had fractured.

As a case of incorrect design, we can mention that of some square cells 10 x 10 m with a height of 12 m. The walls were of mixed construction: reinforced concrete and brick. The capacity of each cell was 1,120 tonnes. At the moment of

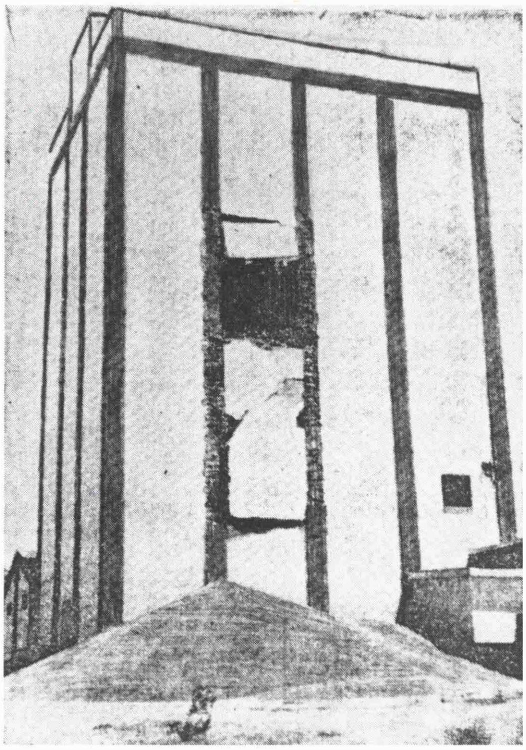


Fig. 10

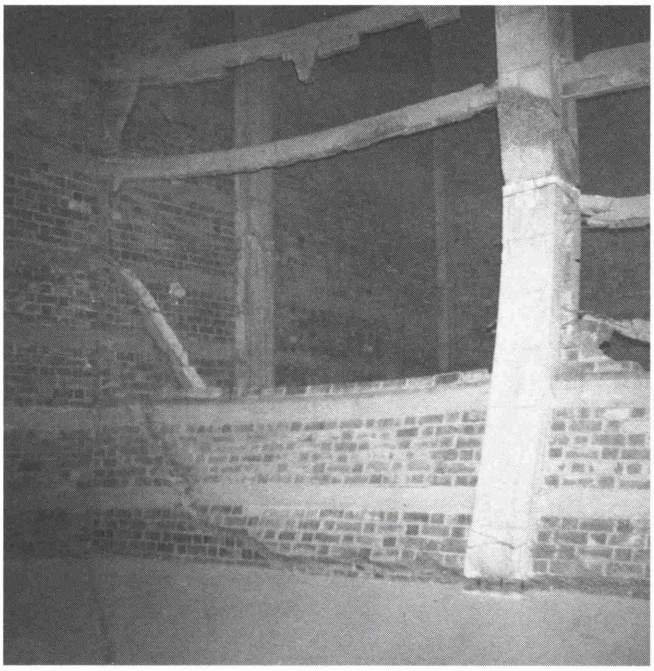


Fig. 12

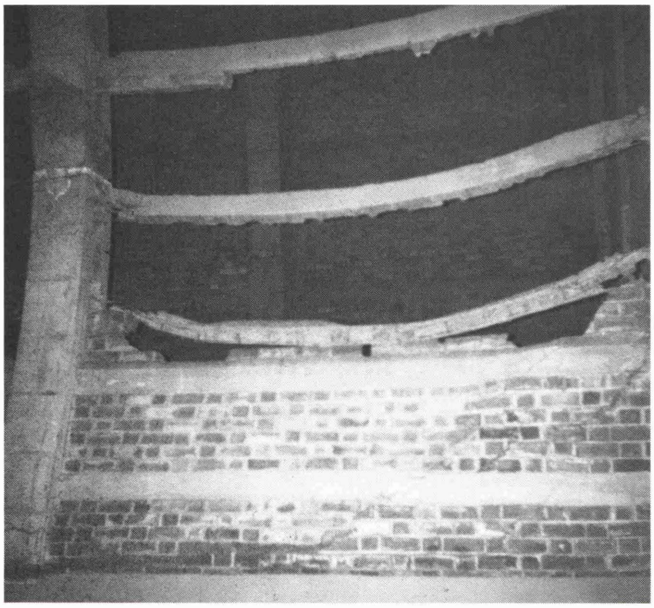


Fig. 11

filling one cell with 740 tonnes, equal to a height of about 8 m, the interior wall collapsed and was completely destroyed, as can be seen in Figs. 11 and 12.

Discharge overpressures were shown to affect the wall at its weakest part, as in the case of a square metal grain silo. In Fig. 13 we can see the deformation produced due to ignoring the local flection of the wave.

Another typical case occurred in a multicellular octagonal metal silo. The dimensions of each side were 3 m and the distance between parallel sides 8 m. The height of the silo was over 23 m.

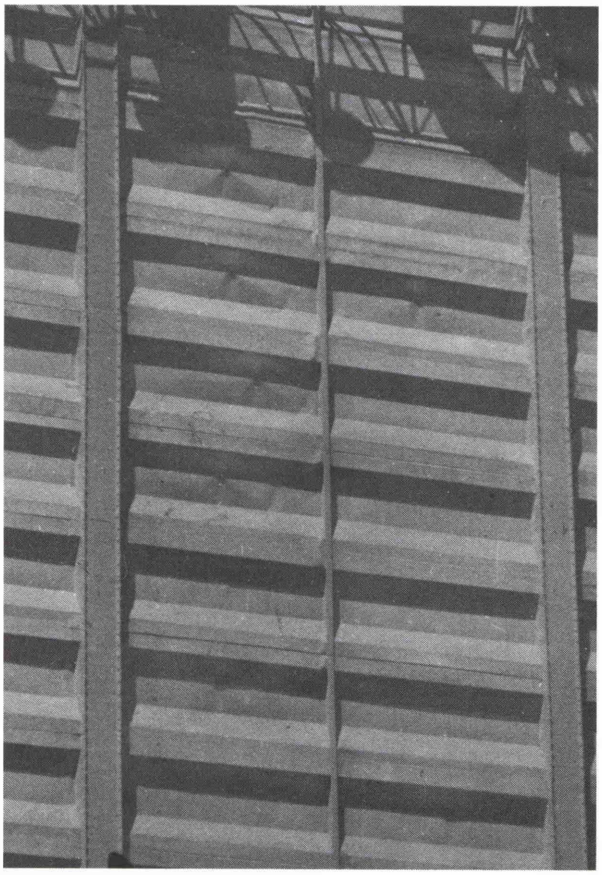


Fig. 13

Once the silo had been filled, it broke when discharge commenced, as can be seen in Fig. 14.

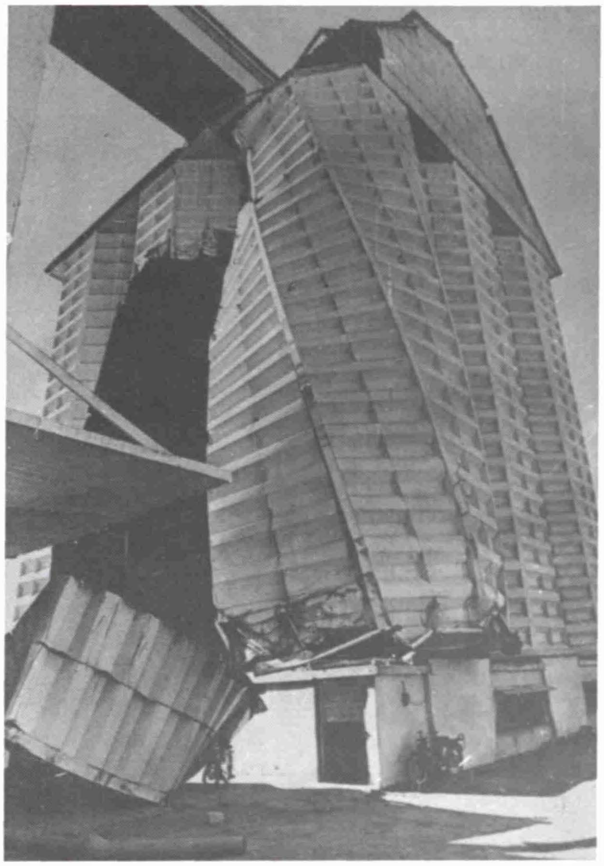


Fig. 14

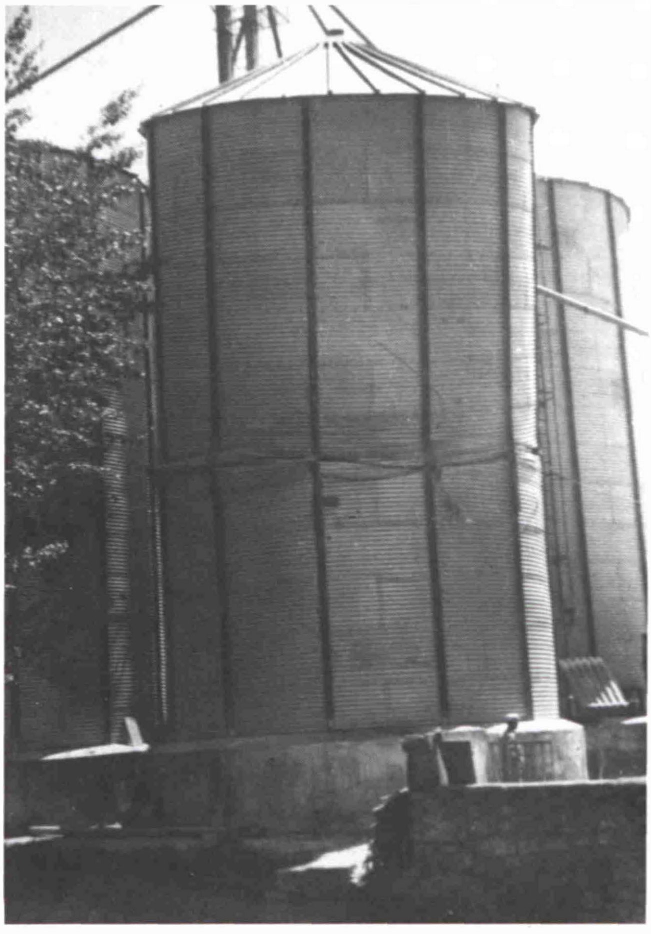


Fig. 15

4.3 Friction Forces

Friction forces acting on the walls of the silo, together with bulging, were the causes of deformation of a grain silo 7 m in diameter and 12 m high shown in Fig. 15.

Another similar case occurred in a cylindrical grain silo 10 m in diameter and 30 m high. Fig. 16 shows the considerable deformation due to bulging of the metal wall.

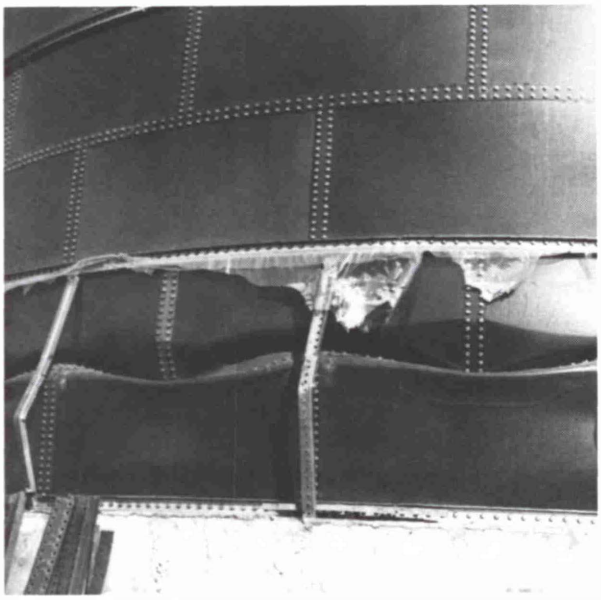


Fig. 16

A silo for storing cement suffered serious deformation and shifted about 60 cm from the vertical after five years in service. Figs. 17 and 18 show the size of the problem.

4.4 Eccentric Discharge

Eccentric discharge directly affects the upright section of the cell, producing ovalisation which results in serious deformation.

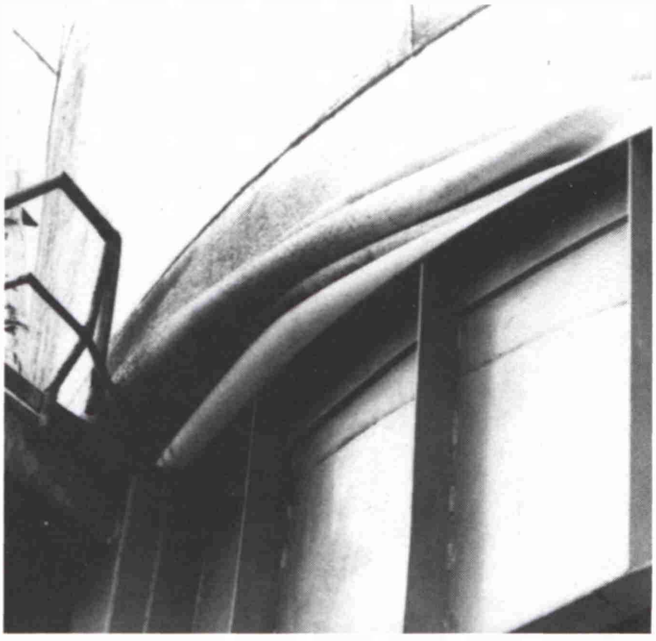


Fig. 17

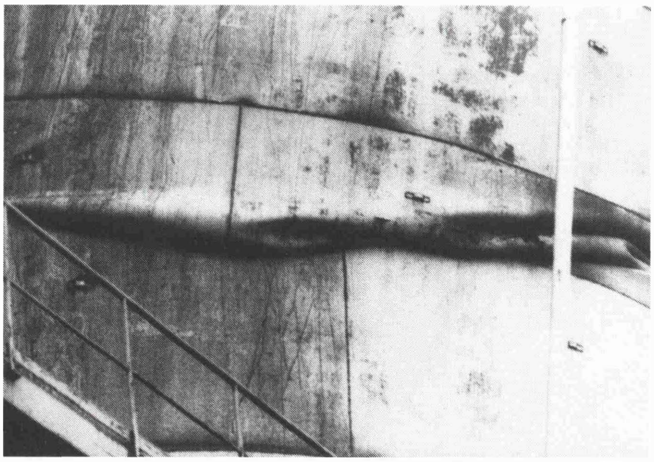


Fig. 18

In cylindrical silos this deformation occurs even when the dimensions are small, such as in the silo shown in Fig. 19 which measures 5 m in diameter and 5 m in height.

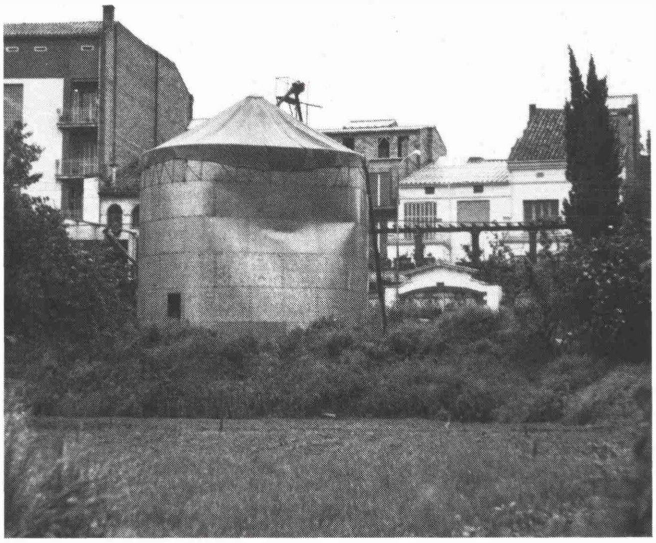


Fig. 19

Eccentric discharge in cylindrical metal silos is highly dangerous since it can cause the installation to fall over. In reinforced concrete silos the transversal rigidity of the walls is much greater and the problem is less serious, except where there is a change of scale and very high silos with large diameters are built; in this case the transversal rigidity of an upright section is reduced.

4.5 Storage of Powder Products

For storage of cohesive powder products, the design of the angle of the hopper, the size of the outlet and the profile (smooth or rough) of the walls is vitally important. These three points, enumerated by Jenike and Johanson, are the key to achieving perfect performance and mass flow; in other words, incorrect design produces flow channels and arches, and the collapse of these gives rise to serious deformations.

Flow channels or pipes may be central (Fig. 20), eccentric (Fig. 21), or eccentrically positioned in a corner (Fig. 22). (Photographs have been taken from above in actual silos.)

Fig. 20

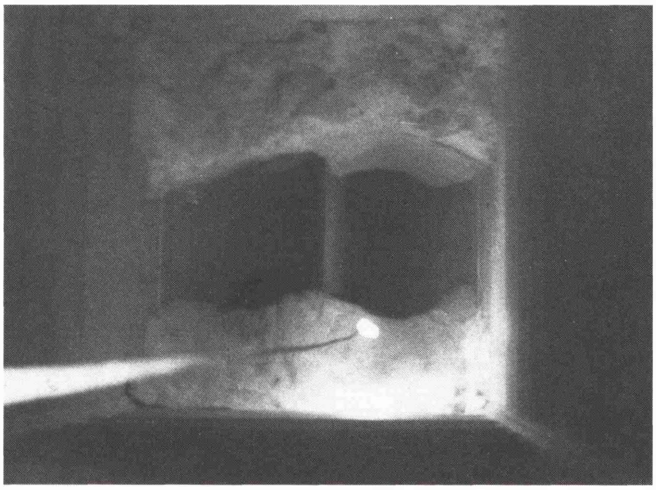


Fig. 21

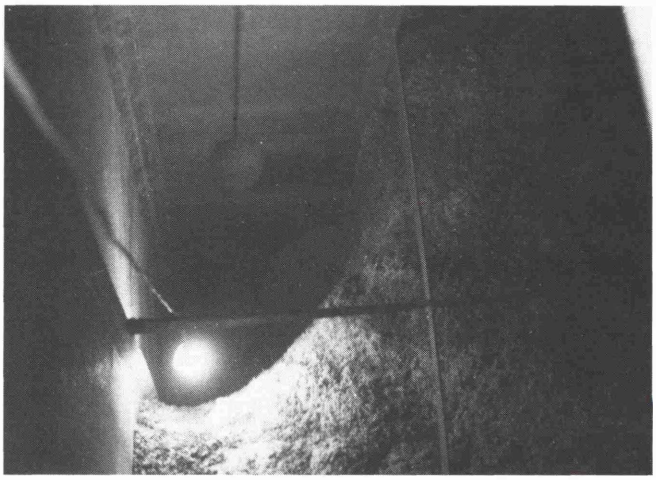


Fig. 22

Normally, when outflow is not correct, arches form, and when these collapse they produce considerable overpressures in the lower part of the cell, together with deformation, as can be seen in Fig. 23. The stored material acts as a piston and produces a considerable depression in the upper part of the cell causing the wall to bend inwards, as can be seen in Fig. 24.

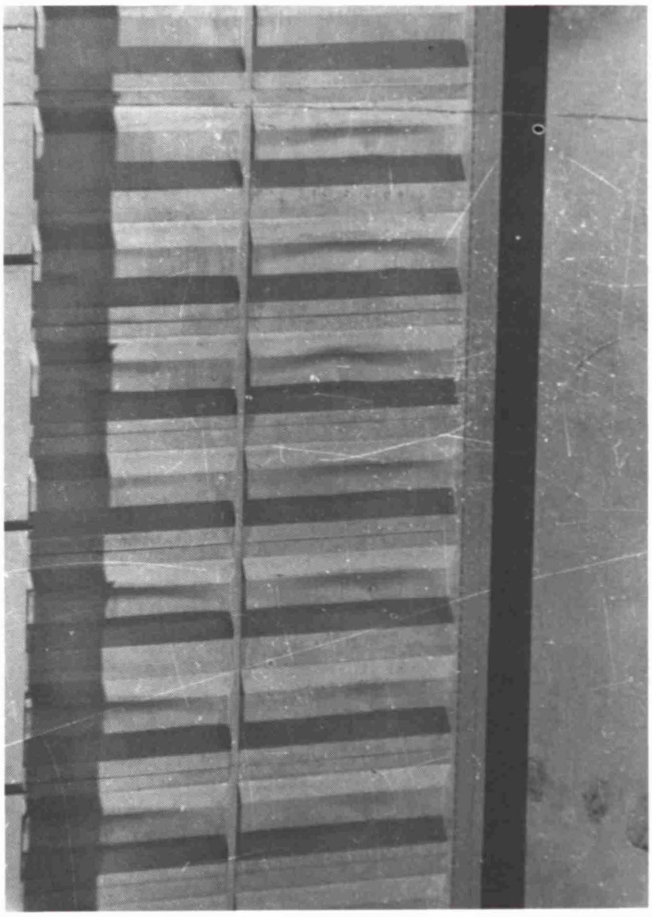


Fig. 23

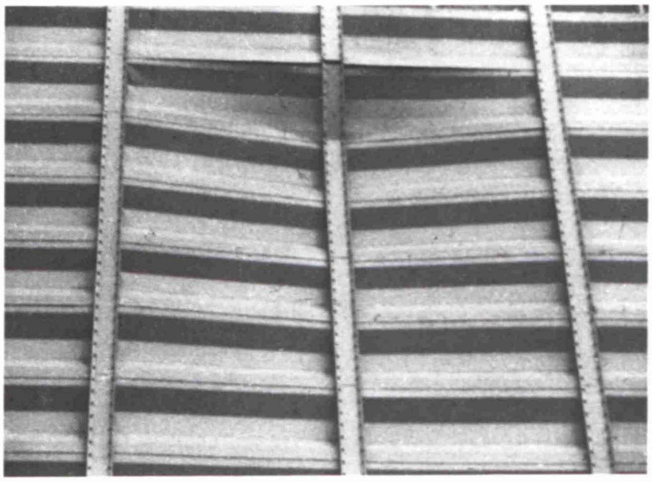


Fig. 24

Where the formation of arches occurs in silos for storing powder materials, in the medium and long term the walls will deform or crack. This is the case of cylindrical reinforced concrete silos for storing soya flour, measuring 6 m in diameter and with a height of 20 m. Cracks occurred after 10 years in service, as can be seen in Fig. 25. Repairs consisted of fitting metal rings to withstand the considerable traction forces (Fig. 26).

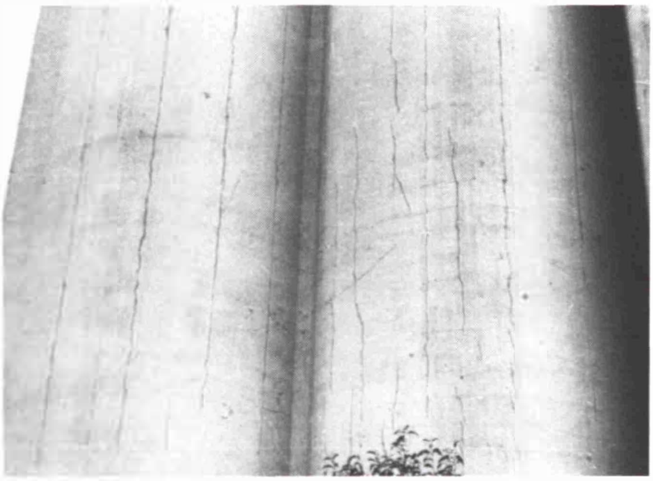


Fig. 25

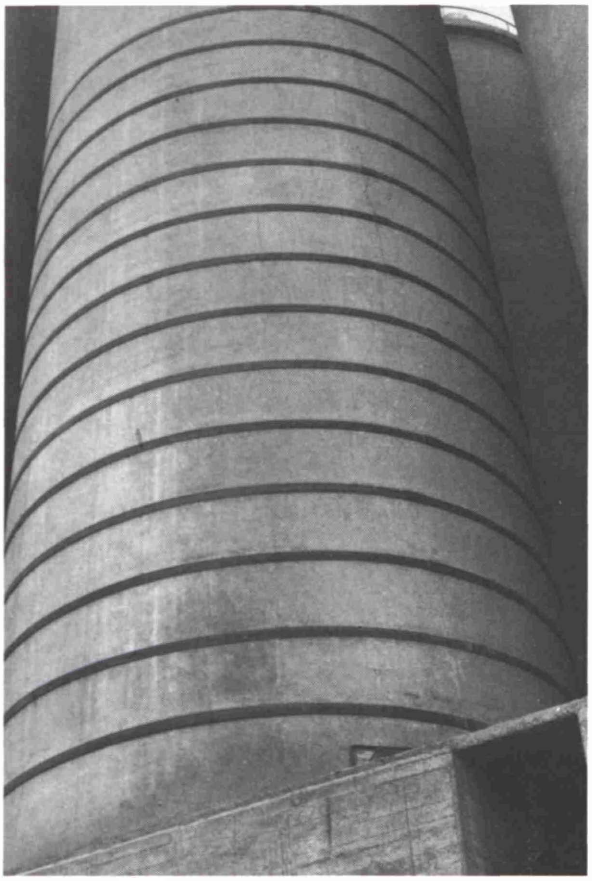


Fig. 26

The same problem arises in a smaller size installation where the walls are made of reinforced brick. Fracture also occurs, as can be seen in Fig. 27.

Fig. 27

In cylindrical metal flour silos with central outlet, the deformation of the walls (Figs. 28 and 29) shows the curve of maximum forces, which are 45 ° on one side of the hopper and 45 ° on the opposite side. These deformations indicate the plane of fracture of the ensiled material at the moment when discharge commences.

In Fig. 30 we can see how the piston effect also occurs in very small silos with diameters of 1.5 m, and how the upper depression causes deformation of the roof.

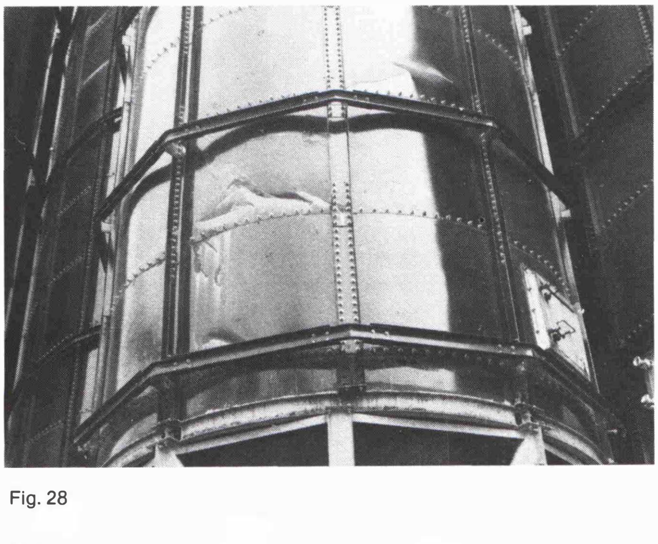


Fig. 28

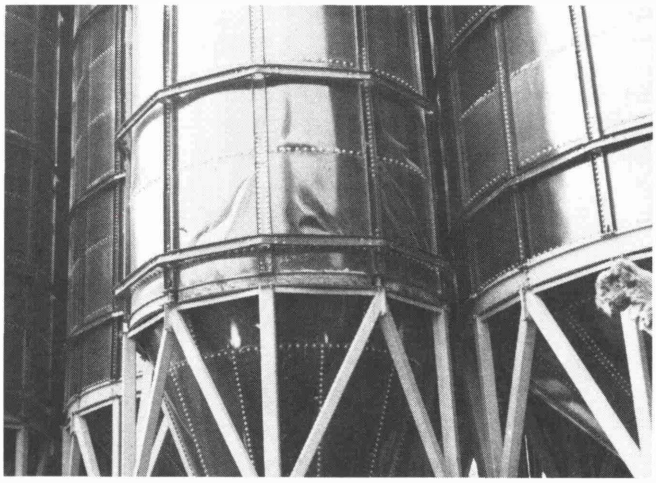


Fig. 29

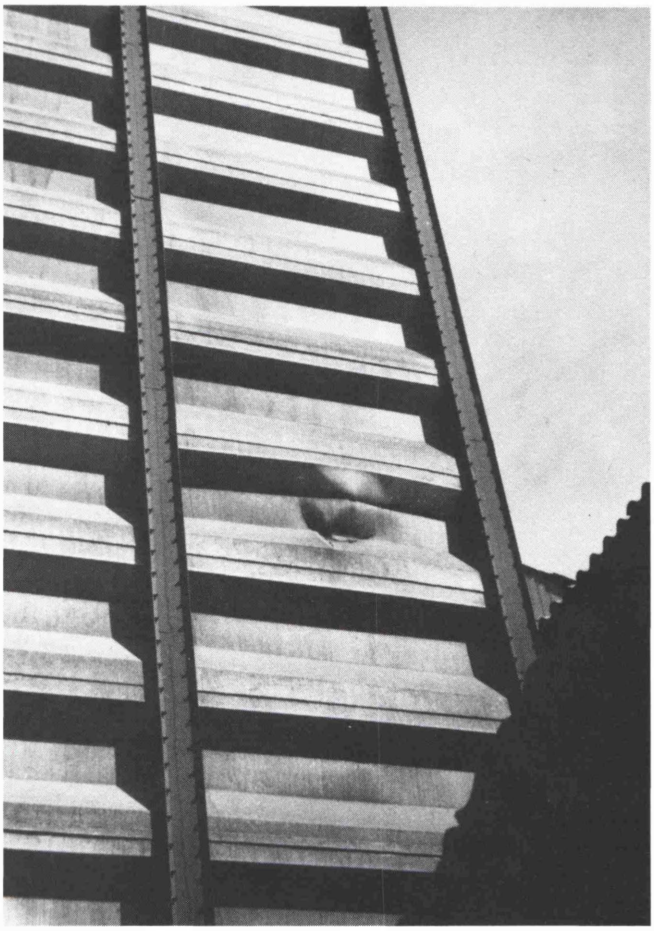


Fig. 30

Finally, we shall consider accidents which have occurred in large silos in the United States during the last few years.

- In Kentucky, a reinforced concrete silo 18.30 m in diameter and 54.90 m high was filled for the first time. Fig. 31 shows the installation, which consists of four outlets with four extractors. When discharge commenced, a series of cracks appeared two-thirds of the way up the silo; these increased in size and number, and within a few minutes the silo collapsed in a heap of coal, concrete and iron. Outflow changed when emptying started, creating a new load state — see Fig. 31.

— In Montana, two silos 21.42 m in diameter and 54.90 m high showed signs of serious deformation of the walls of the order of 33 cm after two years in service. In Fig. 32 we can see the silo emptying eccentrically and producing ovalisation of up to 33 cm. Large cracks appeared, and it was necessary to repair the silo and modify the hoppers in order to achieve mass flow and central outflow.

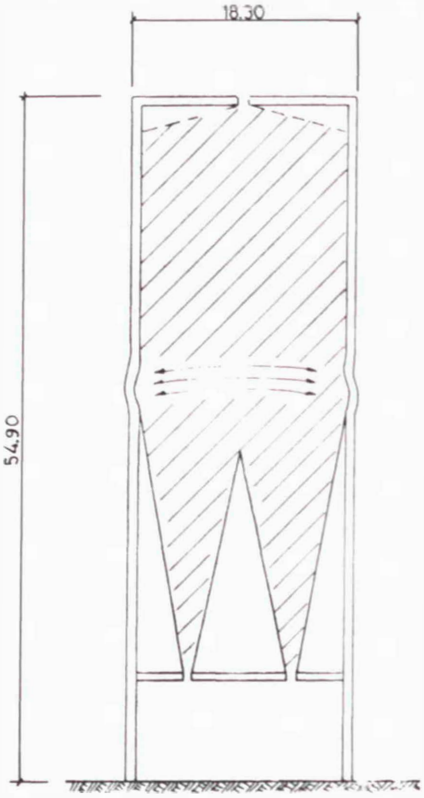


Fig. 31

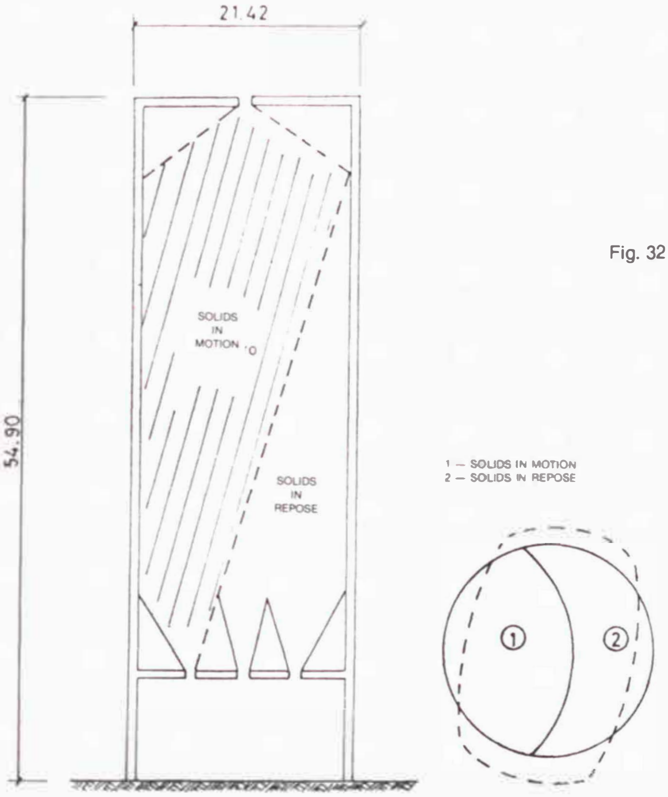


Fig. 32

— In Washington, a silo 18.30 m in diameter and 36.60 m high designed for coal storage. Discharge by means of 4 outlets and stainless steel hoppers at an angle of 60 °.

After a period of time during which eccentric discharge occurred, leaving 50 % of the silo unemptied with the coal forming a vertical wall, the silo collapsed completely — see Fig. 33.

— In Kentucky, a silo 21.42 m in diameter and 47 m high for storing coal, which had been in service for 8 years. When the silo was filled with 12,000 tonnes of coal, discharge commenced; after 800 tonnes had been emptied, deformation occurred around the perimeter of the silo at a height of 6 m. The reinforced concrete wall, 27 cm thick, began to fracture and the silo collapsed completely within a few minutes — see Fig. 34.

— A 17.70 m diameter, 34.50 m high coal silo in Kentucky, with four outlets. Ovalisation occurred in the 25 cm thick walls, together with cracks on both the interior and exterior surfaces (Fig. 35).

— In Texas, a silo 12 m in diameter and 30 m high for storing polyethylene, designed with two elongated outlets and metal hoppers with walls at an angle of 45 ° painted with epoxy resin. Discharge could take place through each outlet independently, producing an eccentric flow channel which deformed the wall, with large cracks appearing through which the polyethylene poured out (Fig. 36).

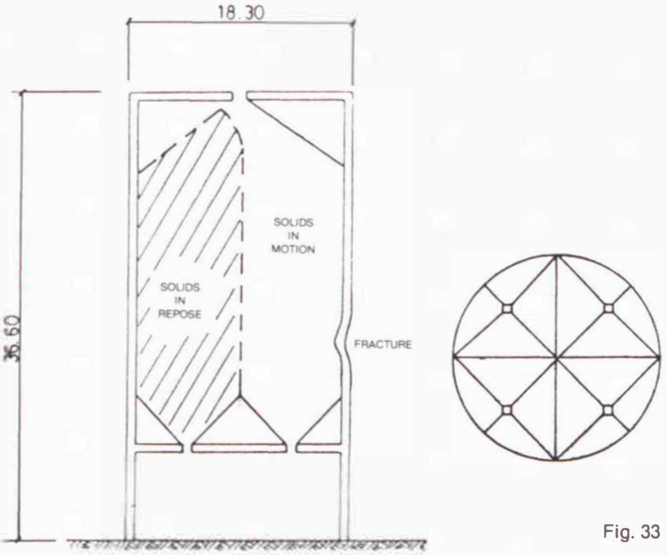


Fig. 33

Repairs consisted in modifying the hoppers by centering them and reinforcing the damaged area.

— In Ohio, a silo 7.20 m in diameter and 25.2 m high. When discharge commenced, an arch formed over the outlet leaving a large area of empty space. When the arch broke, the silo wall fractured, producing a 2 m breach which caused the silo to collapse (Fig. 37).

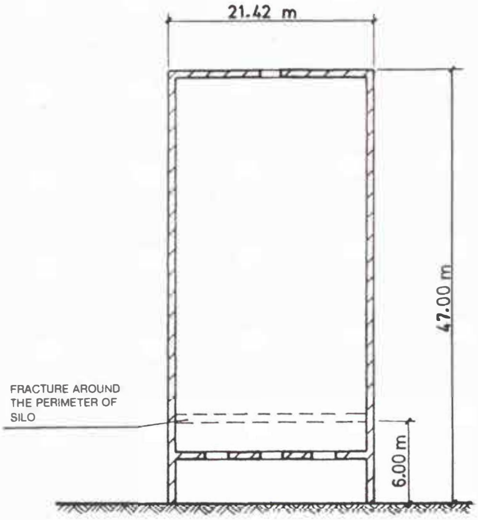


Fig. 34

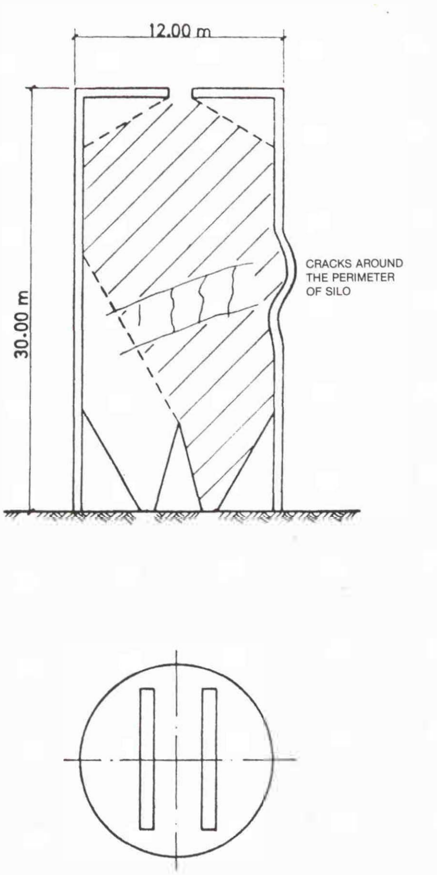


Fig. 36

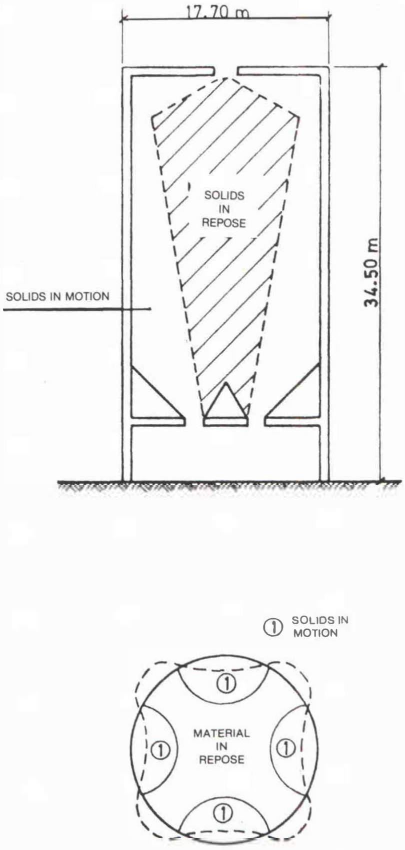


Fig. 35

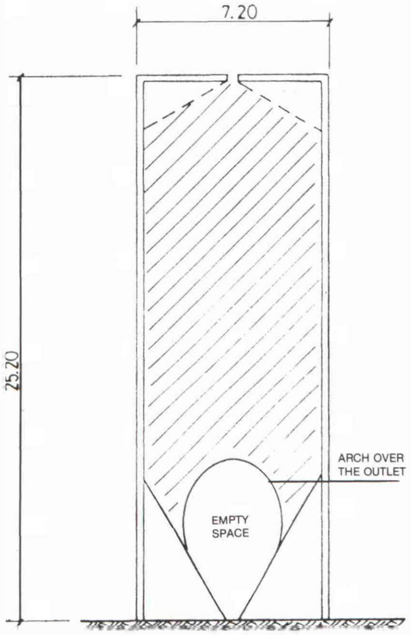


Fig. 37

5. Conclusions

Silo design is the most difficult of all subjects in the field of civil engineering, and proof of this are the constant deformations, fractures and collapses which have appeared all over the world. It is extremely important not to forget any of the factors which intervene in calculations:

- — Study of foundations on the basis of borings.
- — Stability in the face of wind effects, earth tremors and eccentric loads.
- — Calculation of lateral pressure during filling and emptying; pressures on the bottom and friction forces.
- — In the case of eccentric discharge, checking transversal rigidity particularly in metal silos which deform easily due to non-uniform lateral pressures.
- — Storage of granular products gives rise to overpressure coefficients whose envelope is 2.32. Only Jenike and Johanson's theory gives coefficients of over 6, although these are at sporadic points and are due to the wave of overpressure. Transmission per square meter of pressures does not exceed the coefficient of 2.32.
- — Storage of cohesive powder products has caused the greatest number of deformations, crackings, fractures and collapses in the last decade. One of the greatest risks appears when a stable arch forms over the outlet. Collapse of the arch produces the so called piston effect, with very high overpressures in the lower part of the silo and depressions in the upper part.

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