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The Development of Industrial Silos Throughout the World During the Last 100 Years

Juan Ravenet, Spain

It was exactly 100 years ago, in 1881, that Baker started to investigate the lateral pressures exerted by a solid. Nevertheless, it is said that the initial steps towards the automation of flour mills were taken with the construction in 1780 of the first bucket elevator.

In England in 1882, Roberts carried out the first tests to determine lateral and vertical pressures in silos. He built a square silo 3 m wide and 15 m high, together with models for laboratory tests. The results of the tests showed that pressures on the bottom attain a maximum value after the level of the material reaches a height equal to twice the width of the bin. Lateral pressures follow the same procedure. Moreover, there are friction forces on the walls which transmit considerable compression forces.

These tests caused a sensation in their day, since the calculation of silos had been carried out on the basis of hydrostatic pressures; that is to say, the value of both the horizontal and vertical pressures being the product of height multiplied by density. No friction forces were considered, and therefore the weight of the ensiled material rested entirely on the bottom of the silo.

In 1895 Janssen, in Germany, established the mathematical expression of the tests carried out by Roberts. Lateral pressures are of an exponential type, reaching maximum value at a height not exceeding twice the width of the silo. Vertical pressures are obtained by using the value $K = Ph/Pv$ for the ratio between horizontal and vertical pressures. K takes on various values, and in some cases complicated formulae have been used to calculate it.

Fig. 1 shows the ratio between K and the angle of internal friction according to the following authors: Coulomb and Rankine's theory, Jaky, Walker, Frazer.

As shown in Fig. 1, for an internal angle of friction of a given value, the value of K may vary widely, which leads to some uncertainty when calculating vertical pressures.

According to Janssen's theory, for very deep silos (with a ratio of height to width or diameter of over 7) the lateral pressures obtained are only 10% of those calculated in accordance with the formula for hydrostatic pressures.

In 1897, Airy in England calculated lateral and vertical pressures on the basis of the following variables:

Density

Angle of internal friction

Angle of wall friction.

This resolved the uncertainty of the value of K, since Airy did not use it in his calculations. He was the first to distinguish between:

— Deep bins: those in which the flow funnel meets the wall before it cuts the upper surface; a specific formula for the calculations of pressures was established.

— Shallow bins: those where the flow funnel cuts the upper surface of the stored solid before it meets the bin wall. Specific calculation formulae were similarly established and can be found in specialised treatises.

In 1904, Jamieson (Canada) made tests on models using manometers to measure pressures. His conclusions were as follows:

— Lateral pressures obtained in silos with smooth walls were greater than those obtained in silos with rough or corrugated walls.

— Lateral pressures obtained during filling were of the exponential type defined by Janssen.

— No overpressures were noted on emptying, since the increases were not above 2%.

— The results on eccentric outlets were: no variation in pressure on the wall opposite the outlet. On the wall nearest the outlet there was a depression of 50%. Analysis of this result in 1981 helps us to resolve the enigma of calculating pressures in the case of eccentric discharge, which even today leads to considerable confusion between engineers and computing clerks.

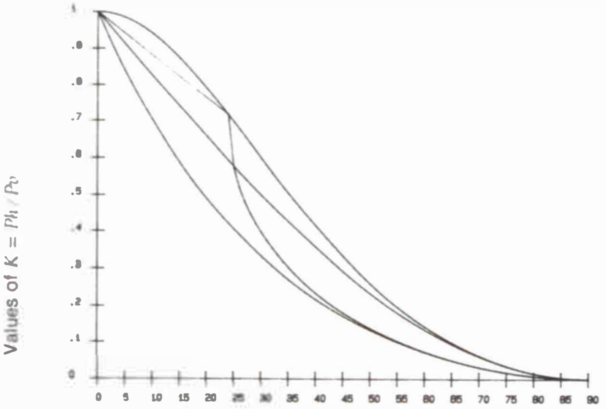


Fig. 1 Angle of internal friction ϕ_i

From then onwards, large silos of reinforced concrete, reinforced brick and metal began to be built. These were mainly constructed around the Great Lakes area between Canada and the United States and in the grain receiving centres of Europe.

In the case of reinforced concrete silos, these were built with a wall thickness of 30—40 cm, diameters of up to 10 m and heights of 40 m. The materials used consisted of reinforcement with a working stress of 1,200 kg/cm², and concrete with a compression stress at 28 days of 150—180 kg/cm². Sliding forms, which appeared around 1915, were used in construction, and it can be seen from specialist technical journals of that period that silos with capacities of up to 30,000 tonnes were erected in a fortnight.

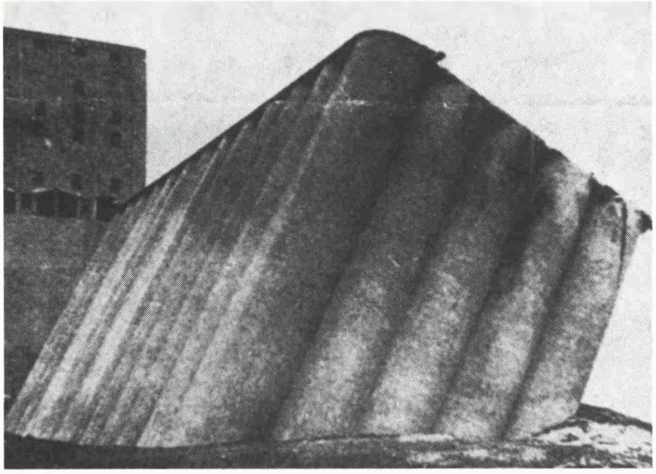


Fig. 2

Parallel with the construction of large numbers of silos, the first problems appeared, as can be seen in Fig. 2 which shows a 35,240 m³ grain silo at Transcona (Canada). Building took from 1911 to 1913. In October of that year, when it was being filled with 31,500 m³ of grain, representing 94% of its total capacity, the silo collapsed and overturned (Fig. 2). The ground load envisaged was 3 kg/cm², and the actual pressure at the moment of collapse was 2.17 kg/cm². The problem arose through ignorance of the existence of a layer of muddy clay at a depth of between —6 and —10 m. The silo acted like a monolith. It was restored and brought into service again in 1916 as a great feat of engineering skill.

Fig. 3 shows another problem that appeared in concrete silos, due to failure to take account of overpressures on emptying. The concrete cell has broken. In other cases concrete cells have cracked right across (Fig. 4).

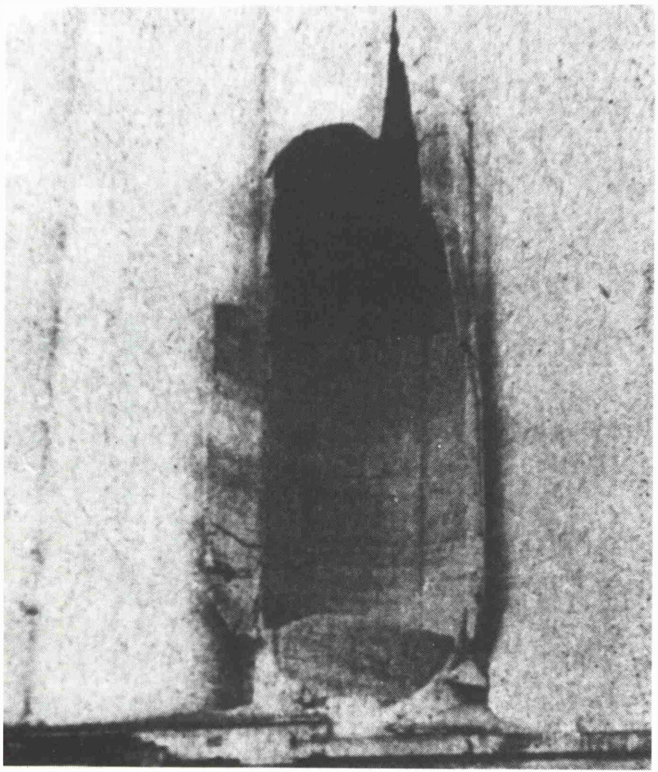
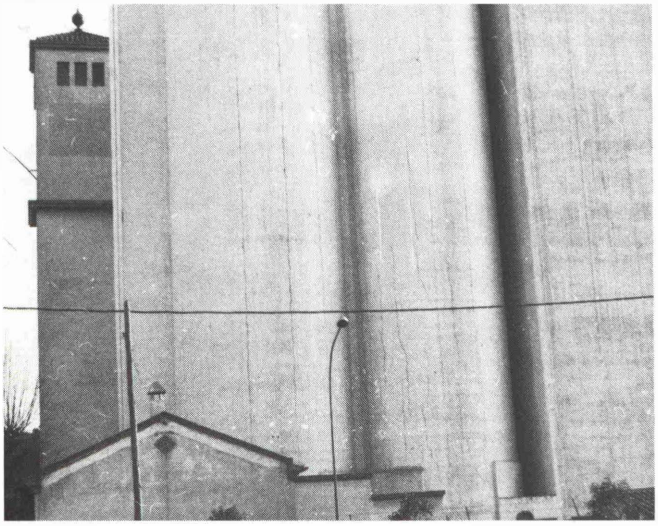


Fig. 3

Fig. 4


The use of low quality concrete and reinforcement, or of materials which do not correspond to the specifications on which calculations are based, or where construction work has not been properly carried out, often leads to unpleasant surprises, such as the complete fracture of a cell as shown in Fig. 5.

In 1943, M. and A. Reimbert presented the results of tests on models for determining the forces of power materials (or rather, granular materials) on silo walls. This study was carried out because of accidents which had occurred in cylindrical reinforced concrete grain silos where cracks had appeared particularly in the upper parts or in the area of suspension of the hopper (Fig. 6) due to considerable dynamic forces produced during emptying. Reimbert established his own theory for calculating lateral and vertical pressures and friction forces. The Chateau London silo (two square bins 4.30 m wide and 10 m high) and the Crecy-en-Brie silo (four octagonal bins 20 m high with a square pocket bin) were built in 1952 and 1953. Fig. 7 shows the deformation which occurred in the walls of the first silo.

Strain gauges were placed in these silos in order to measure lateral pressures, and the results can be seen in Fig. 8. To avoid discharge overpressures, Reimbert designed the decompression tube or static flow pipe consisting of a perforated tube placed inside the silo (Fig. 9) which produced a disciplined emptying by layers, thus preventing the feared discharge overpressures. According to the Swedish specialist, Bergau, static flow pipes were used for the first time at the beginning of the century by Miersch in the Frankfurt/Main silos. Duhle used them in the Alexandra Dock (Liverpool) silo; and they were also used by Huart and Kvapil.

Ravenet carried out tests on transparent models using a static flow pipe (Fig. 10), and after several attempts he

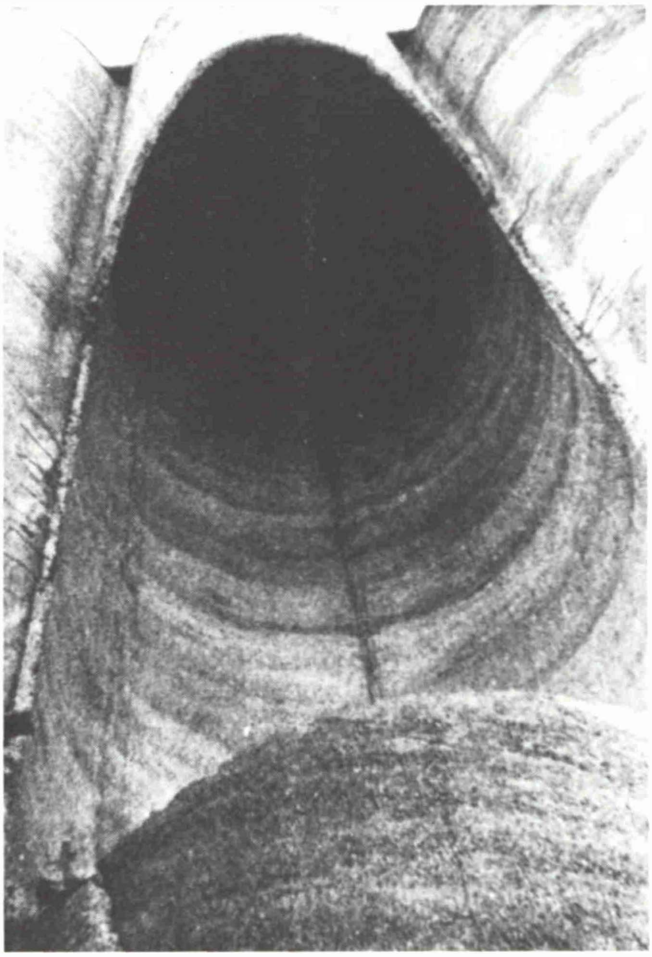


Fig. 5

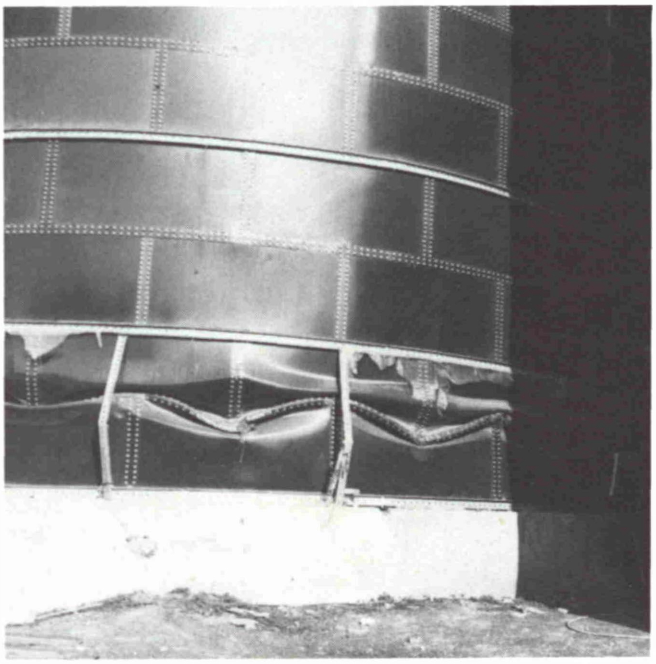


Fig. 7

Fig. 6

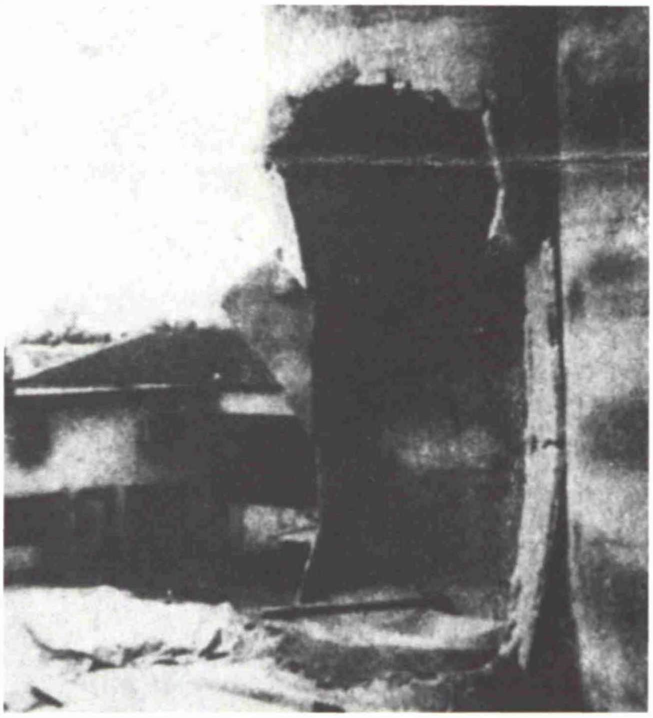
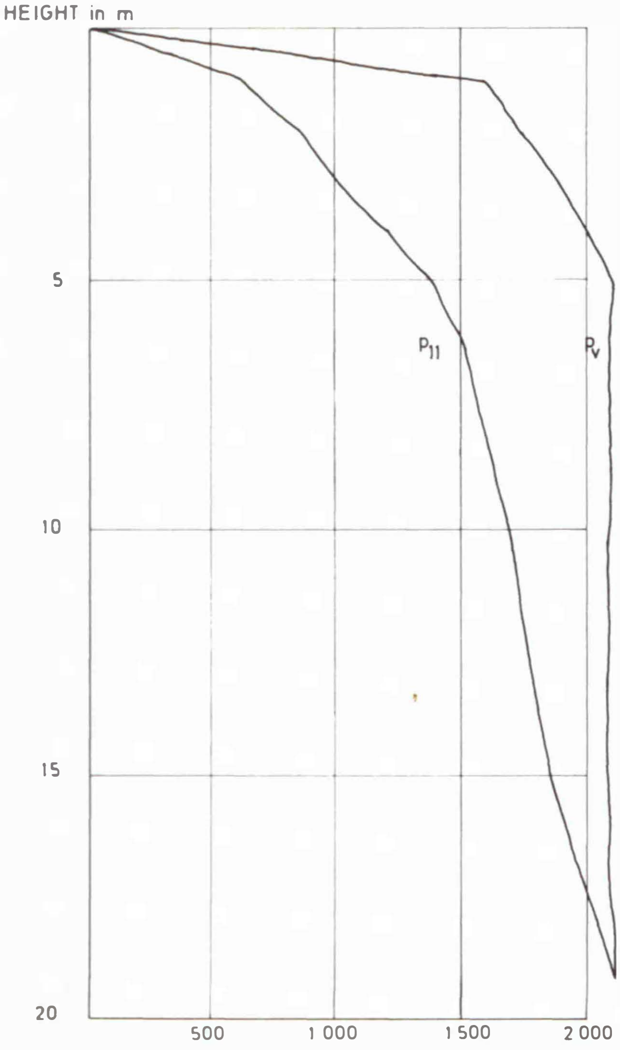
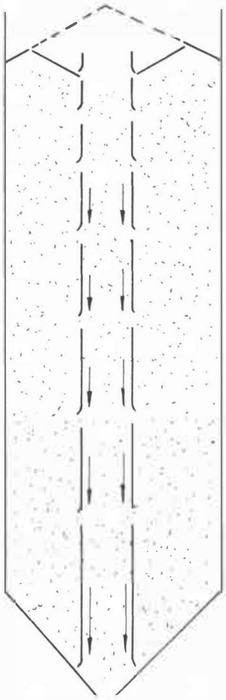


Fig. 8





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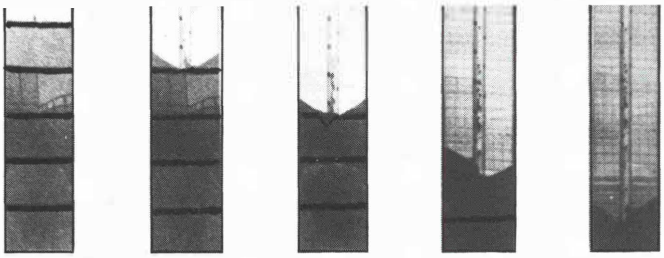
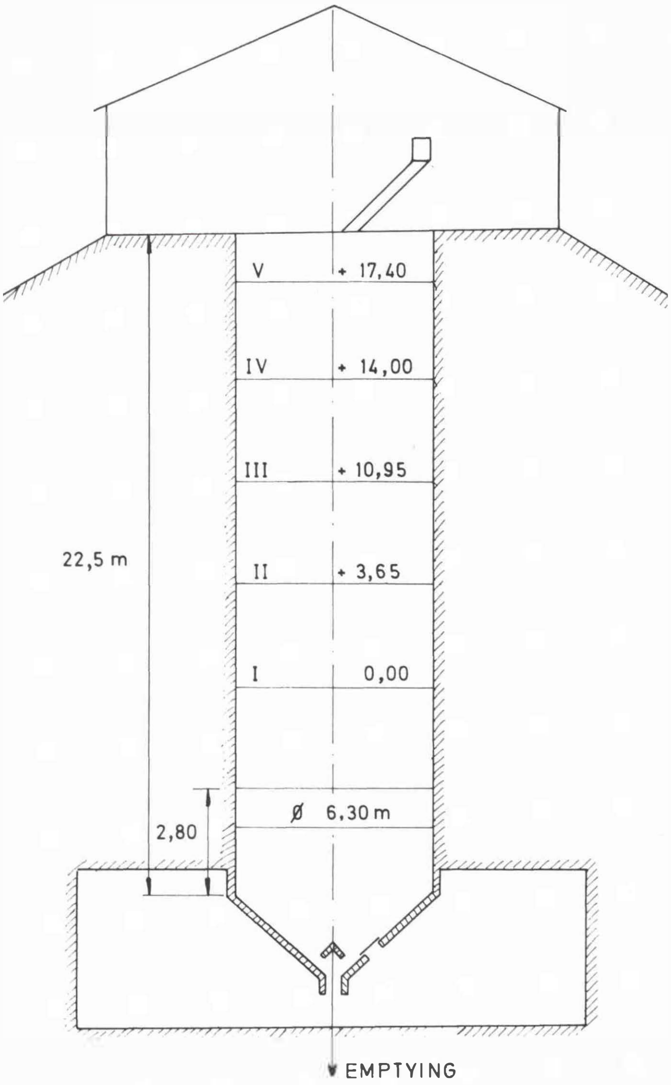


Fig. 10



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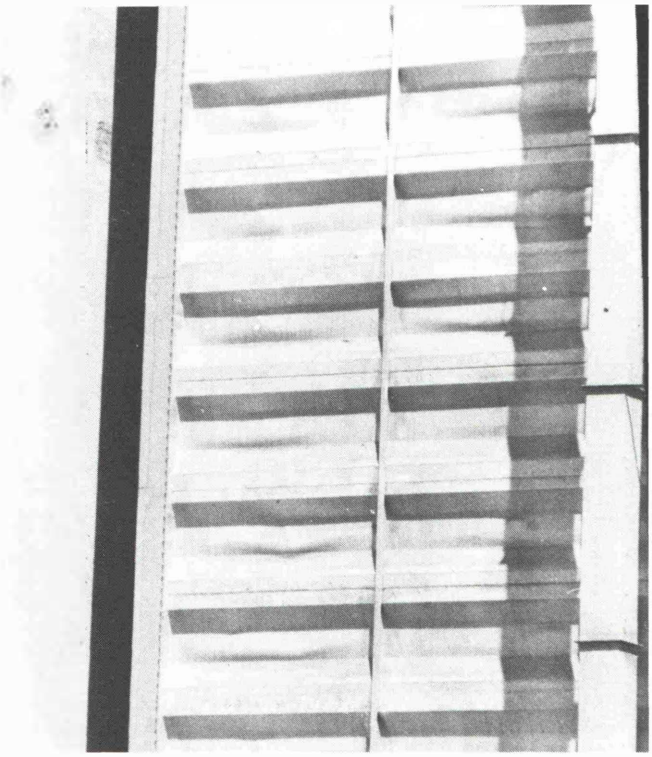


Fig. 11

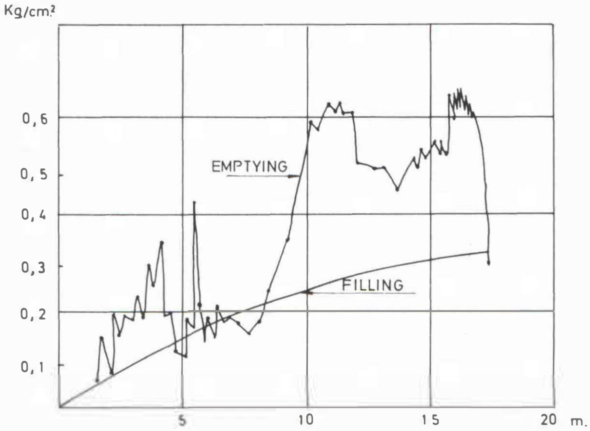


Fig. 13

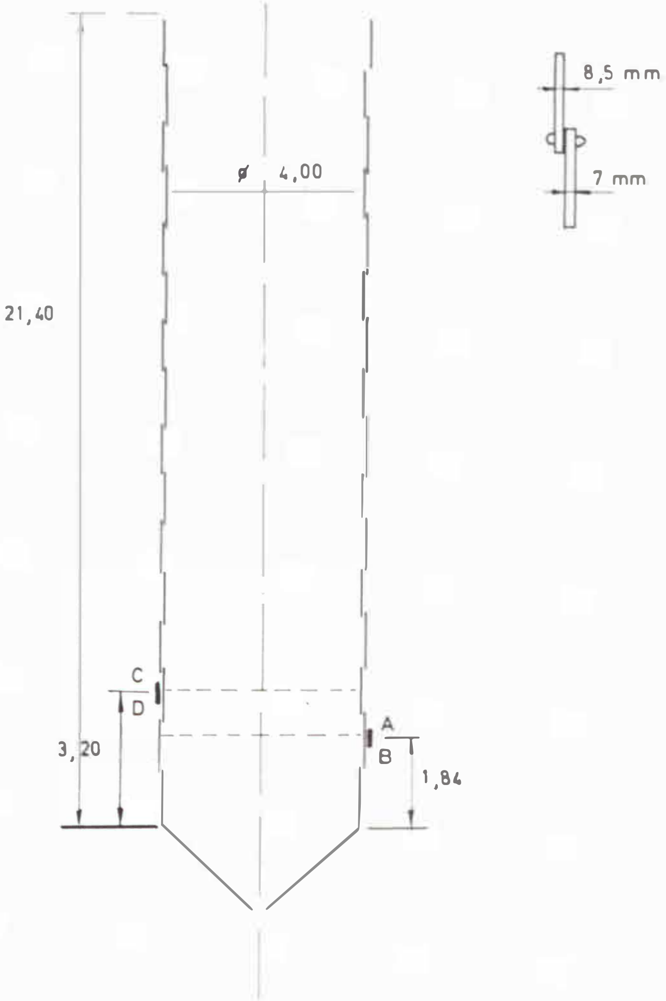
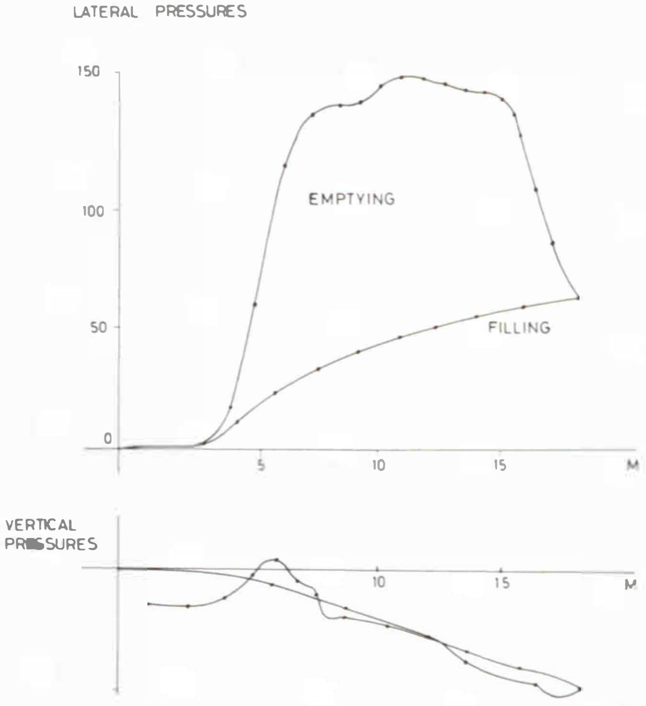


Fig. 14



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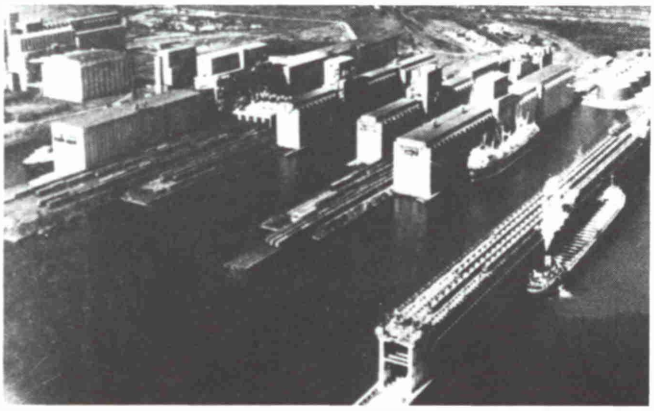

Fig. 16

achieved the desired result — discharge in layers. Nevertheless, the system suffers from two disadvantages:

1. Discharge: To what extent is it of interest that the last mass in is the first out? Fermentation can occur in the lower part of the silo due to the product remaining there for too long, particularly if it is not in good condition.
2. Structural problems: If the decompression tube fails — which happens fairly often because the holes get blocked up — or the product becomes compacted on account of excess humidity or dirt, then free flow occurs, together with discharge overpressures which in the medium term deform the silo walls (Fig. 11).

Tests carried out by Ravenet on models in which strain gauges were placed showed that, in one cell with static flow pipe, Janssen's pressures occurred during filling, and on emptying there was an overpressure coefficient of 1.35.

Bergau and Kallstenius carried out tests on life-size silos in Sweden in 1959:

1. A reinforced concrete silo with a diameter of 6.30 m and a height of 22.50 m (Fig. 12), where strain gauges were placed at 5 different levels, obtaining an overpressure coefficient of 2 (Fig. 13).
2. A metal silo 4 m in diameter and 21.40 m high (Fig. 14), where an overpressure coefficient of 2.37 was obtained (Fig. 15). Here the readings were only taken at 3.20 m from the bottom with two strain gauges.

Kallstenius carried out the first tests on outflow in transparent models in order to see the influence on discharge of the size of the outlet.

Zakrzewski, the Polish engineer, was consultant for nine installations in South Africa. He applied overpressure coefficients of 2 and did not use static flow pipes since the saving did not compensate for safety. He applied a value of $K = 0.33$ and carried out tests on transparent models to determine the outflow.

Around 1960, large capacity silos were built in the Great Lakes area of America, as can be seen in Fig. 16. Various problems occurred both in the foundations and in the structure of the silos, for reasons such as:

— Discharge overpressures.
— Incorrect design of cells and pocket bins.
— Unexpected pressures on the bottom.
— Friction forces higher than those calculated.
— Eccentric outlets.
— Explosions.
— Collapse of arches in ensiled power products.
— Wind effects.

In Fig. 17 we can see some of these problems and their unfortunate and fatal consequences.

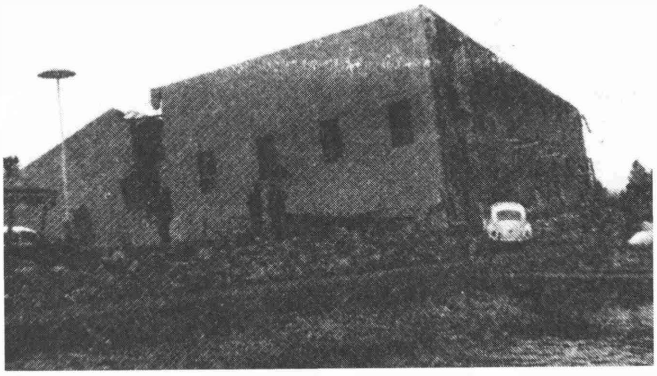

Fig. 17

In 1963, Turitzin published an article recounting the experiences of the main Russian specialists such as Takhtamishev, Kim, Geniev, Kovtum and Platonov. The overpressure coefficient allowed was 2.32 for granular products, and can be considered as the maximum curve of all curves produced by world specialists.

Lenczner made an interesting study in 1963 on models, using sand as the test product, and obtained a value of $K = 0.20$.

In 1964, Laforge and Boruff studied the flow speed of particles in relation to the type of outlet. In Fig. 18 we have a flat-bottomed silo: there is a central area of high speed flow and a large part of the material remaining static.

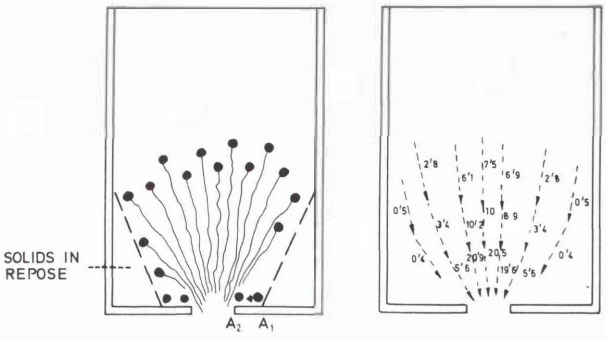

Fig. 18

Fig. 19 shows the case of a hopper with a 20° angle of incline. The speed of the particles diminishes rapidly, outflow decreases, and unstable arches form over the outlet.

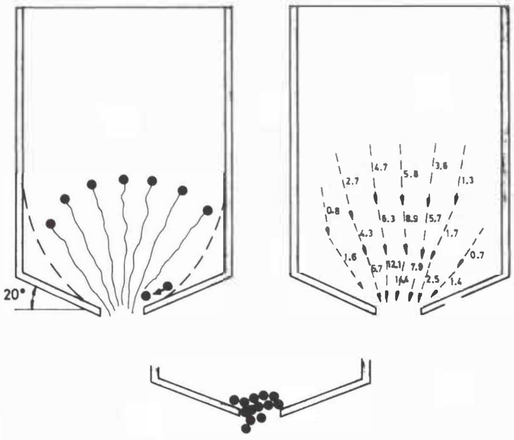

Fig. 19

In Fig. 20 we have a 60° hopper which produced a more uniform discharge with increased flow.

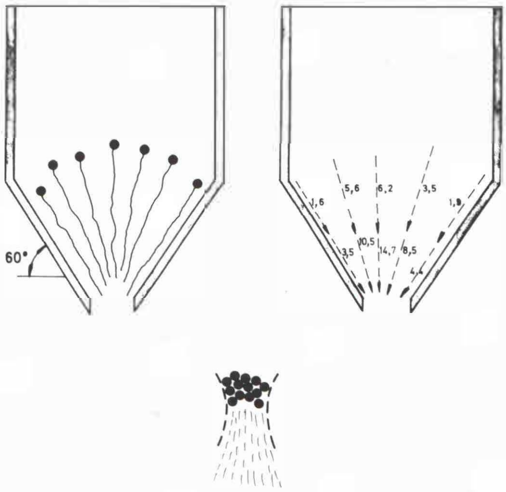

Fig. 20

In 1964, the DIN 1055 Code appeared, which determinted lateral and vertical filling and emptying pressures on the basis of density and internal angle of friction. The formulae are of an exponential nature and take values of $K = 0.50$ during filling and $K = 1$ during emptying.

In 1965, Kvapil established an outflow in the form of an elliptical revolution with two semi-axes, and considered four clearly defined zones (Fig. 21):

- — Slip surface (1)
- — Feed zone (2)
- — Discharge ellipse (3)
- — Material in repose (4)

In the case of an eccentric outlet, the ellipse was practically halved (Fig. 22). In order to avoid having material in repose within the silo, a multiple outlet was designed with distances "p" being less than "c" (Fig. 23).

In 1967 Handley did his doctoral thesis at the University of Sheffield with tests on circular and rectangular models, using a radiosensitive pill placed inside the silo with the test material to measure vertical pressures and wall pressures. In Fig. 24 we can see the results of his tests and the way in which lateral pressure varied widely at the intersection of the bin and hopper, with a depression appearing.

Parallel with these tests and experiments, construction commenced in Spain of small wooden silos for flour mills and for storing flour and other by-products. A timid start was made on the construction of square and cylindrical reinforced concrete silos. Around 1942, the National Wheat Board (SEMPA) began massive construction of reinforced concrete or brick silos of square cross-section. The typical picture of a Spanish village shows the church and silo rising above the rooftops.

These silos were calculated in accordance with Janssen's theory, without taking into account discharge overpressures or eccentric outlets. The silos are filled and emptied about once or twice a year.

Private firms began construction of reinforced concrete silos on the sliding form system, using German and Swedish techniques.

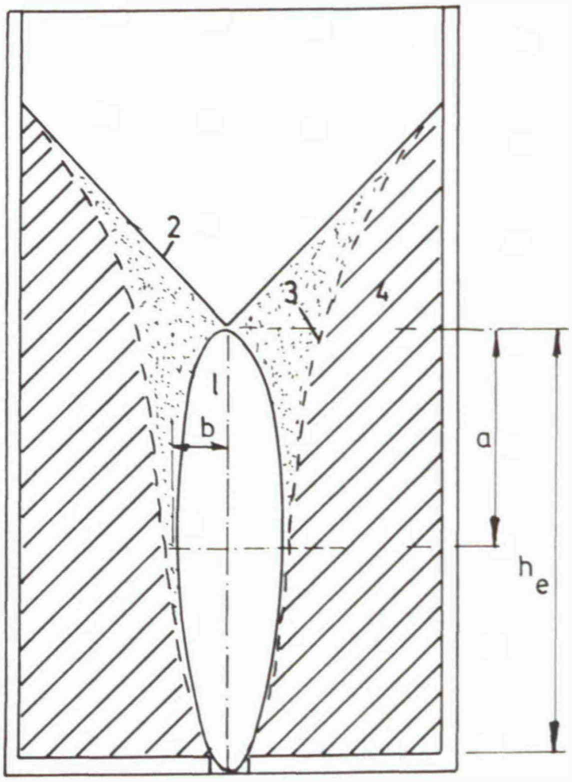

Fig. 21

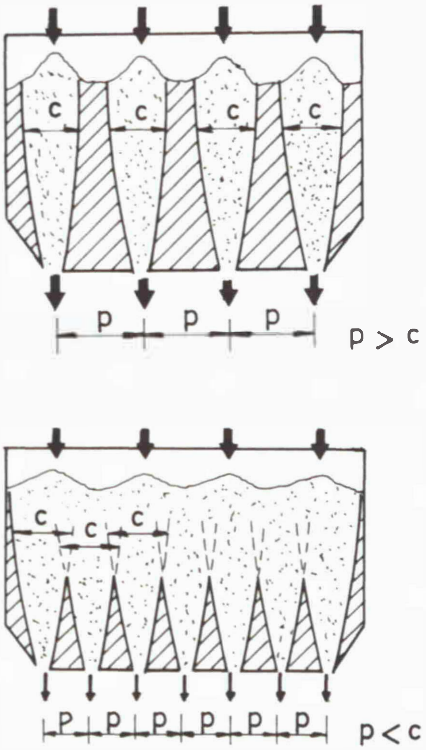

Fig. 23

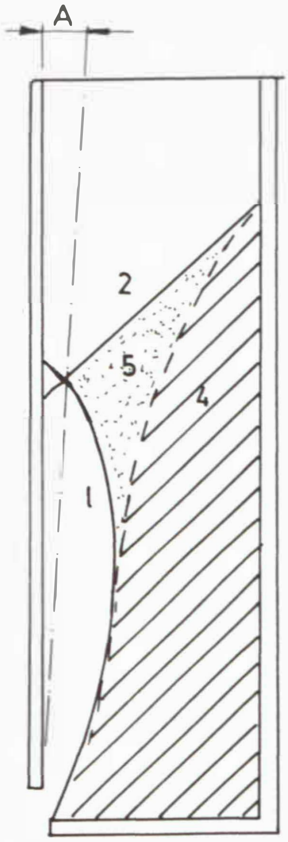

Fig. 22

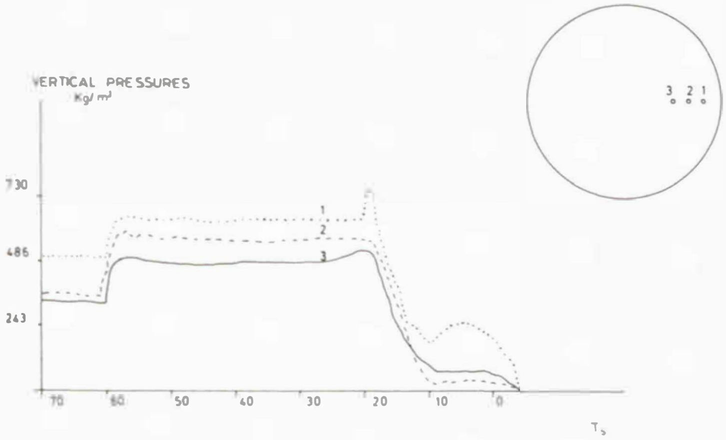

Fig. 24

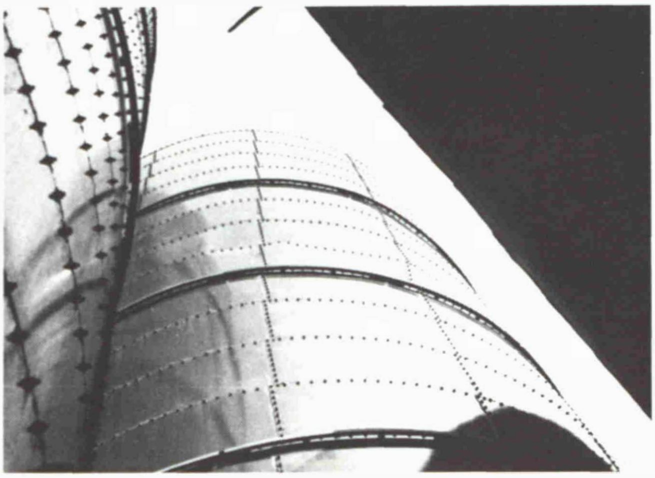

Fig. 25

Construction of metal silos began with three varieties:

1. Cylindrical metal silos made of smooth metal sheet sufficiently thick to withstand stress (Fig. 25).
2. Cylindrical metal silos of thin corrugated sheet (between 0.6 and 3 mm) with vertical reinforcements (Fig. 26).
3. Square metal silos made of corrugated sheet (Fig. 27).

This series of silos was built in accordance with Reimbert's theory, since no other theories or technologies had yet reached Spain.

To continue with events abroad:

Jenike and Johanson's theories appeared in 1968, defining two types of flow as shown in Fig. 28:

- Mass flow: on opening the outlet the whole mass starts to move.
- Core flow: the silo empties in the form of a central funnel, leaving a large quantity of material in repose. Stable arches can form which interrupt outflow; collapse of these can cause high pressures on the bin walls and hopper.

The active state appears during filling (Fig. 29) and the passive state during emptying (Fig. 30). Opening of the outlet causes a wave of overpressures corresponding to the transition between the active and passive states. Maximum pressure is produced at the point where this wave meets the wall (Fig. 31). This effect has been clearly detected by Ravenet in life-size silos (Fig. 32). According to whether barley or maize is stored, the funnel cuts the wall in the centre or above, deforming specific parts of the silo.

In 1969 Pieper, in Germany, made tests on models with strain gauges in order to determine lateral pressures in cases of both central and eccentric outlets, and obtained the results shown in Fig. 33. During testing the formation of unstable arches at various levels was noted, indicating that the weight of the stored mass can be transmitted to the walls by friction.

Another conclusion obtained was the variation in lateral pressure in relation to friction between grain and walls on performing several fillings.

When filling with powder products by compressed air, the angle of internal friction is virtually nil and the mass behaves as a fluid. Lateral pressure is very high. As time passes the air is eliminated from the mass and lateral pressure diminishes.

In 1969 in Germany, Theimer made a comparison of theories according to various specialists and Codes in different countries. He considered that DIN 1055 (1964) was insufficient with regard to sizing, and many silos based on this Code have suffered serious cracking and even deformations. Theimer was able to record that more problems have appeared in silos in recent decades than in those constructed earlier on, and that this is due to the fact that the safety coefficient of concrete and reinforcement has been reduced from 2.50 to 1.75.

In 1969, Safarian, an Armenian by birth and conversant with Russian theories, settled in the United States where he worked as a consultant engineer. In order to determine lateral pressures, he differentiated between metal silos and reinforced concrete silos. He applied a correction coefficient to Janssen's and Reimbert's theories, according to whether the cell was polygonal or circular, unicellular or multicellular; cells or pocket bins, interior or exterior; and according to height-breadth ratio.

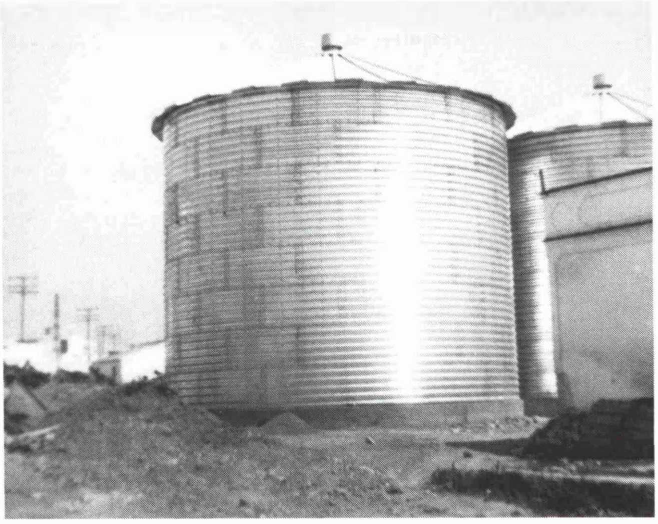
Fig. 26

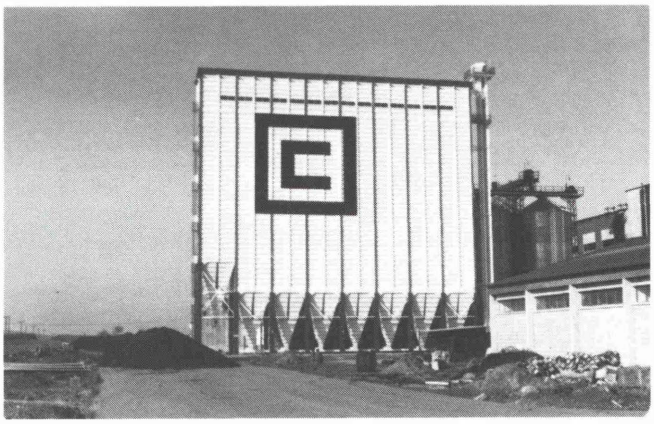
Fig. 27

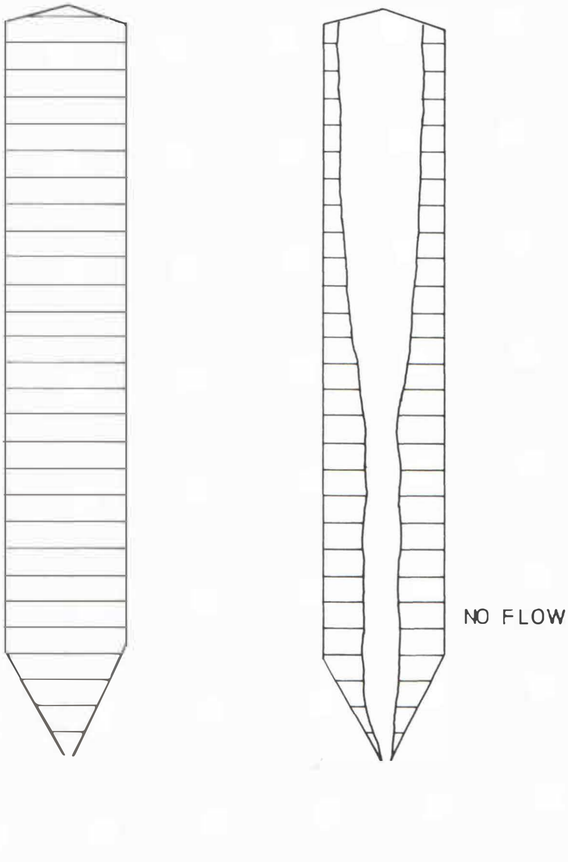

Fig. 28

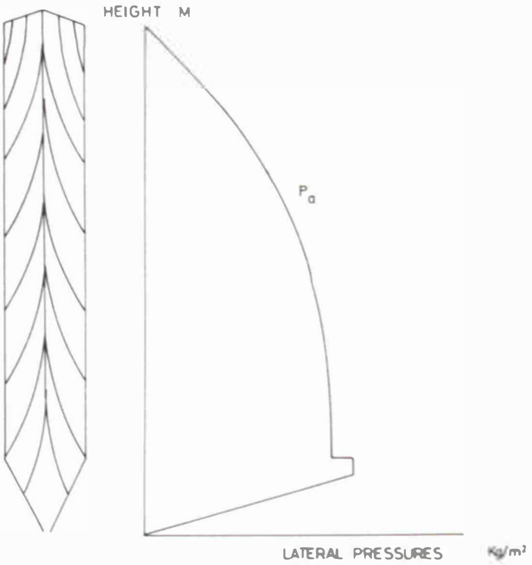

Fig. 29

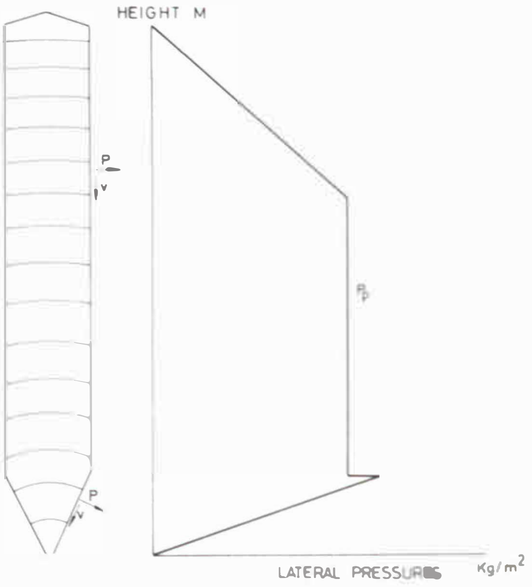

Fig. 30

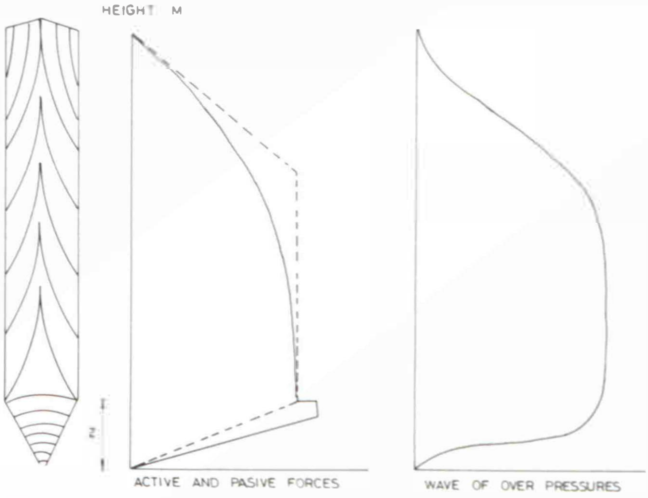

Fig. 31

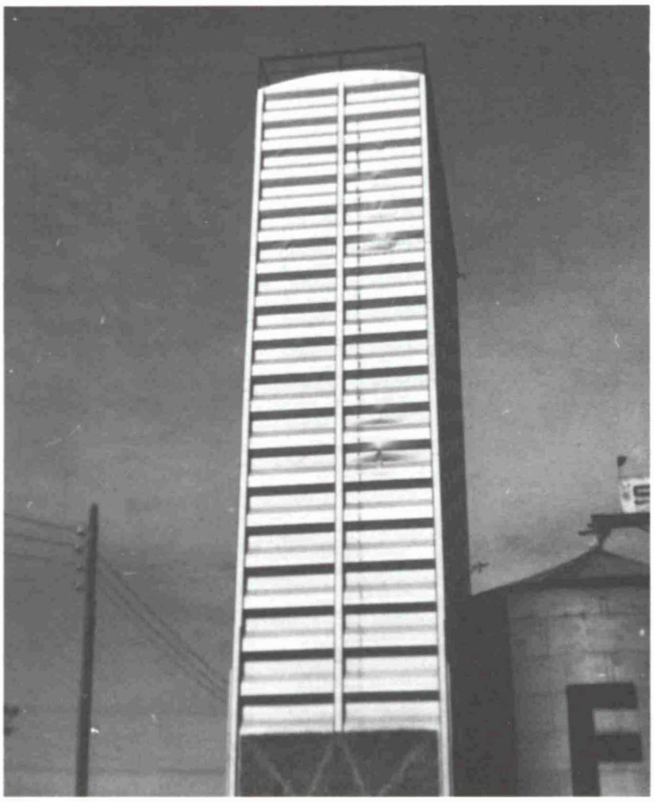

Fig. 32

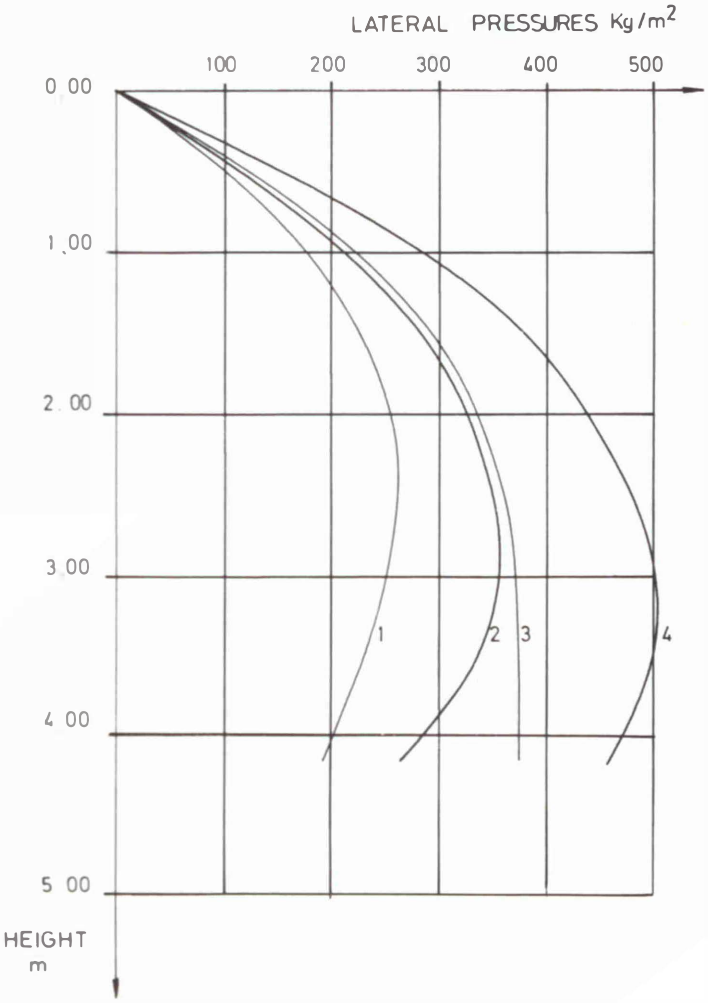

Fig. 33

In 1970 in France, Lumbroso was the only foreign specialist to mention the variation in density in relation to diameter and height of the silo. For example, a silo 12 m in diameter showed the following densities:

Wheat:	830 kg/m³ at a depth of 15 m 1,050 kg/m³ at a depth of 30 m
Cement:	1,430 kg/m³ at a depth of 15 m 2,000 kg/m³ at a depth of 30 m
Sand:	1,800 kg/m³ at a depth of 15 m 2,400 kg/m³ at a depth of 30 m

For a silo with central outlet, although we do not know what type of outlet was used (multiple screws, fluidification), the distribution of lateral pressures was not uniform throughout a straight section in the silos at Akmjansk and Octobre (Fig. 34).

Garg (India) in 1972 referred to the Russian Code CH-302-65 which uses Janssen's formula with three coefficients:

N = 1.30, constant for all shapes and silos.
L = variable in relation to the type of silo with a maximum value of 2.
M = ditto, with a maximum value of 0.5.

Silos were divided into the following types:

Single circular silos,
Multicellular silos in line,
Square multicellular silos, with sides not exceeding 4 m.

In Spain at this time (1972), this latter type of silo was being built, and for practically four years the same method of calculation was used. The silos were for storing granular and cohesive powder products.

In 1974, Ravenet did his doctoral thesis on the subject of silos: calculation of lateral pressures in relation to outlet (whether central or eccentric). Tests were carried out on transparent models in order to determine outflow in the following cases:

- — Central outlet, height-width ratio of 7.
- — Central outlet, height-width ratio of 1.5.
- — Eccentric outlet, height-width ratio of 7.
- — Eccentric outlet, height-width ratio of 1.5.

The static flow pipe system has already been mentioned above in connection with Reimbert. Tests were made on a model using strain gauges to measure filling pressures and discharge overpressures.

The result of the tests gives us a coefficient of 1.95, as can be seen in Fig. 35.

The eccentric outlet gave rise to overpressure of up to 95 % on the opposite wall and depressions of 0.76 on the near wall, as shown in Fig. 36.

The tests and experiments were carried out in the Material Strength Testing Laboratory at the School of Industrial Engineering of the Barcelona Polytechnic University, and refer to granular products. They enable one to detect in any type of installation the whereabouts of the areas of highest pressure. These are the danger points which must be controlled and checked during inspection visits.

Silos for storing powder products were beginning to be built in Spain without any design precautions except for the incline of the hopper, which is between 50° and 60°. These recently built silos can be seen in Fig. 37.

The subject of storage of cohesive powder products (mainly flours) has still not been resolved on a world-wide basis, either from the structural point of view or the flow point of view (perfect emptying of the bin). Papers published abroad on this subject, which amount to over 100 articles in recent years, explain complicated theories which do not always work in practice — in other words, there is so far no complete practical solution.

Tests have been carried out on transparent models, and the first point to be noticed is that outflow differs according to the product. Fig. 38 shows the outflow of grain, ground rice and a powder product (with small, medium and high angles of friction).

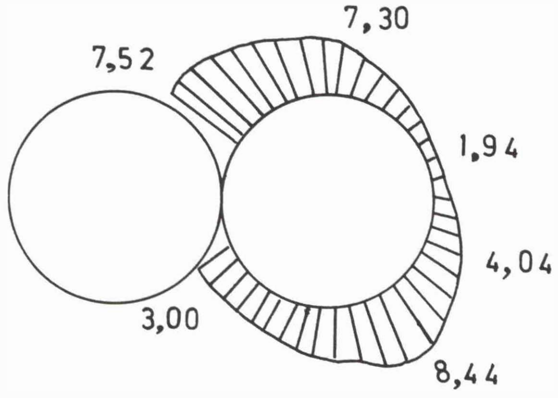

Fig. 34

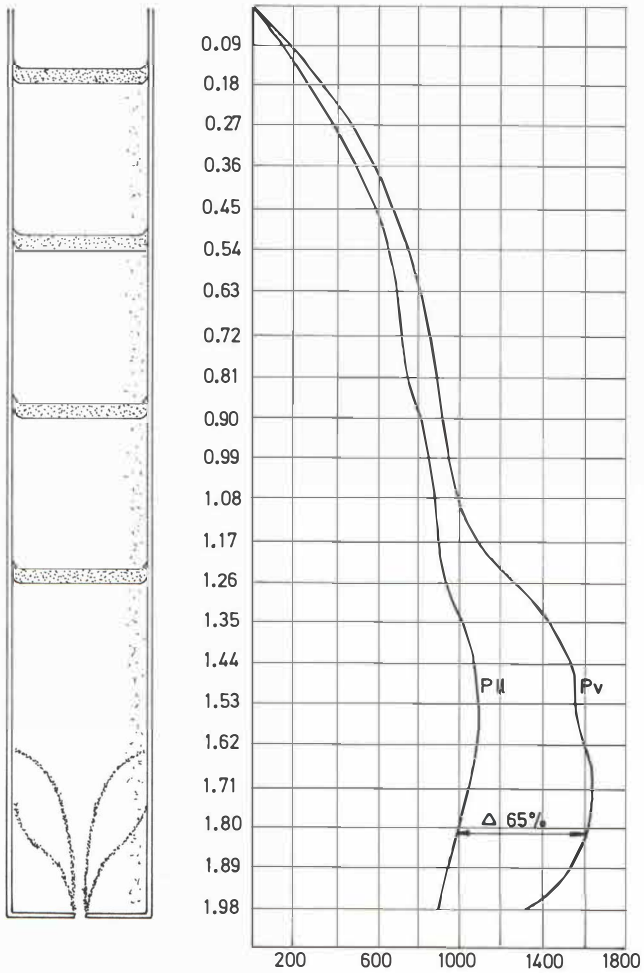

Fig. 35

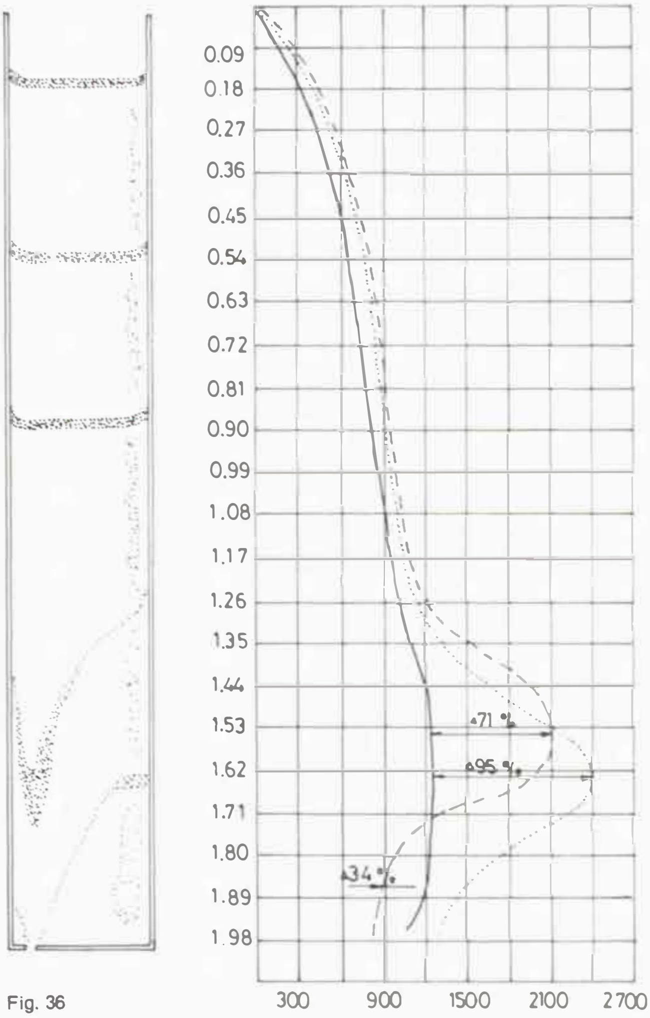

Fig. 36

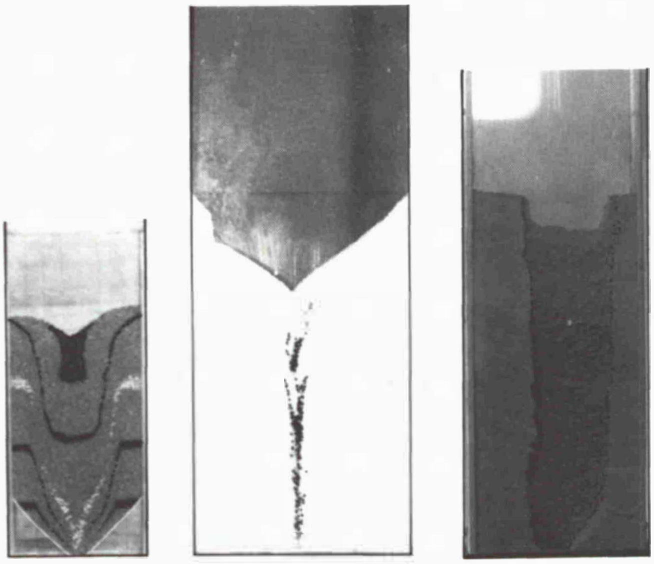

Fig. 38

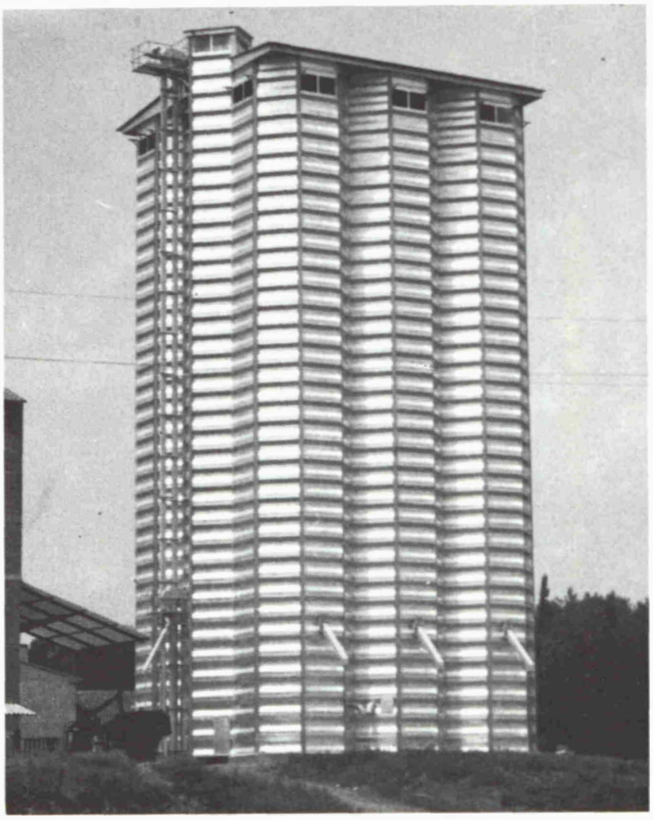

Fig. 37

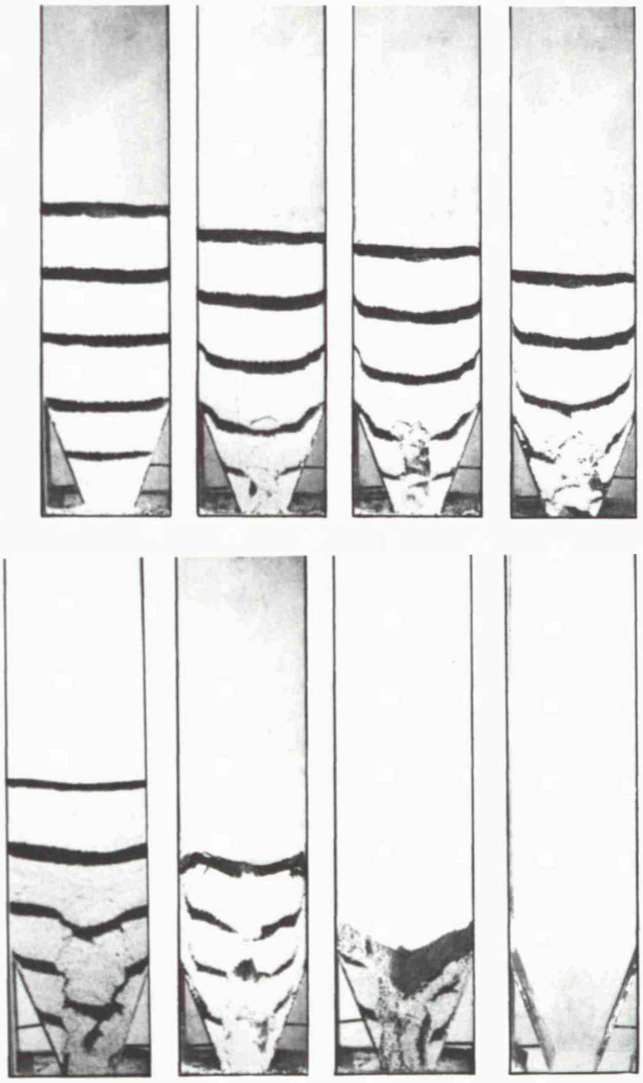

Fig. 39

In Fig. 39 we can see the flow sequence in a model with a 60° hopper (insufficient incline), a small outlet, and where the walls of the hopper are not smooth enough. Stable arches were formed during outflow, which could be broken by tapping the hopper. This typical discharge pattern in the majority of silos built throughout the world causes serious problems of deterioration or fermentation of the product as well as loss of productivity in the factory due to the continued interruptions in outflow.

The problems seen in the model are accurately reflected in full-scale silos (Fig. 40) showing that the model theory is entirely fulfilled in real life (in fact the problem was seen in an actual silo and reproduced in the model). At the end of the year this causes losses in excess of the cost of the installation.

Many flour silos have been designed with eccentric outlets so as to avoid the formation of arches, but a flow channel still appears, leaving large quantities of material adhering to the walls.

In Fig. 41 we have transferred the eccentric outlet to a model and reproduced exactly the discharge process with the formation of a flow channel.

Normal outflow of a product depends on four circumstances, namely:

- Size of outlet.
- Incline of hopper walls; the steeper the better.
- Smoothness of hopper walls.
- Texture of bin walls.

Ravenet has introduced an additional factor consisting of a hopper and counter-hopper, as shown in Fig. 42.

We can see the design of hopper and counter-hopper in full-scale silos in Fig. 43. With this system, mass flow is achieved.

The formation of arches and their subsequent collapse gives rise to high pressures in the lower part of the silo, whilst considerable depressions occur in the upper part.

Problems with silos continue to occur in various countries:

- Brazil: collapse of a silo.
- Britain: collapse of silage bins, and an interesting study of silos in order to determine the friction forces which the wall will support, as can be seen in Fig. 44.
- In the United States a series of enormous silos have been built 15 m in diameter and 60 m high for storing various materials, many of which are cohesive powder products. These silos have suffered serious problems and some have collapsed.
- In South Africa a great many reinforced concrete silos were built some years ago, with a diameter of 15 m and height of 25 m, with such limited reinforcement that the first ones suffered from large cracks. This is a typical and recurrent type of silo, which has been reinforced subsequently.
- In Sweden an inventory was made of existing reinforced concrete silos, and it was found that 30 % were cracked (with fissures larger than the 0.2 mm permitted). Two of these were even found to have water penetration.

In Spain, silos of the type shown in Fig. 45 continue to be built.

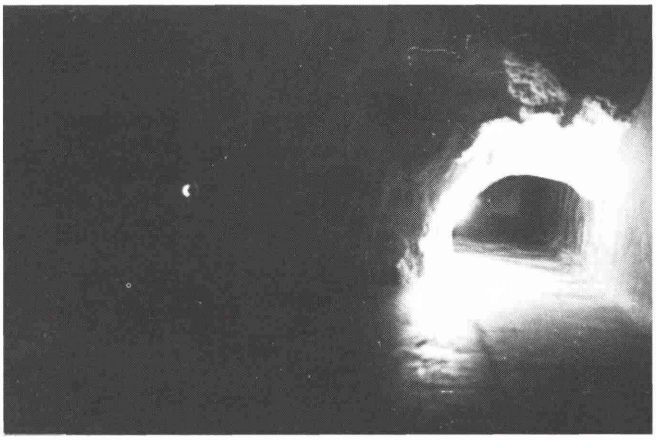
Fig. 40

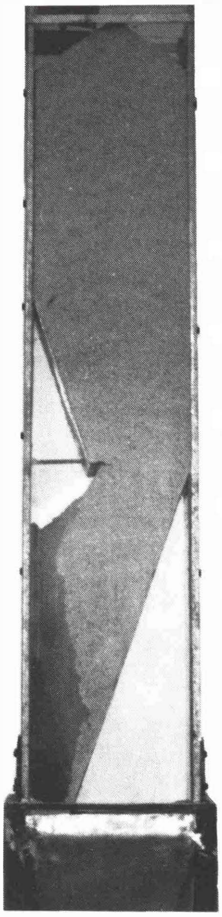
Fig. 41

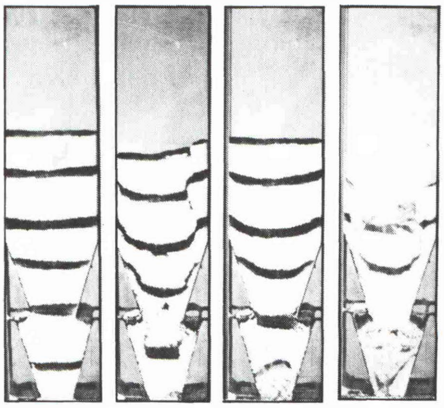
Fig. 42

Fig. 43

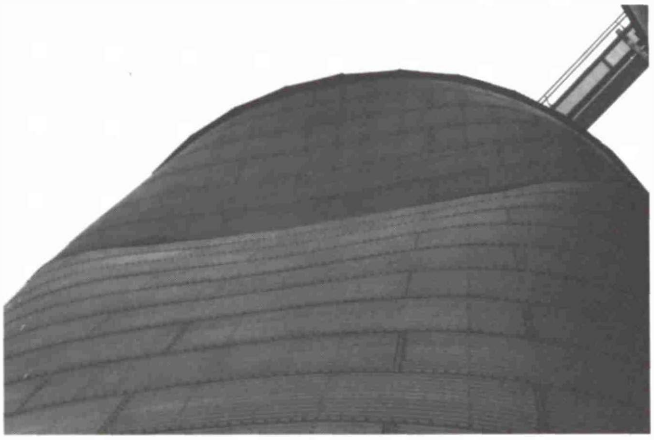

Fig. 47

Fig. 44

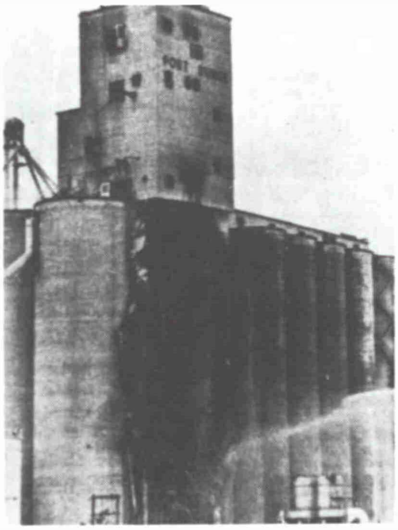

Fig. 48

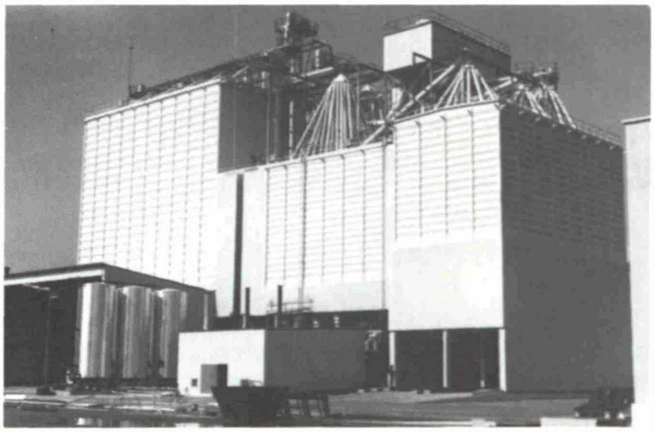

Fig. 45

Fig. 49

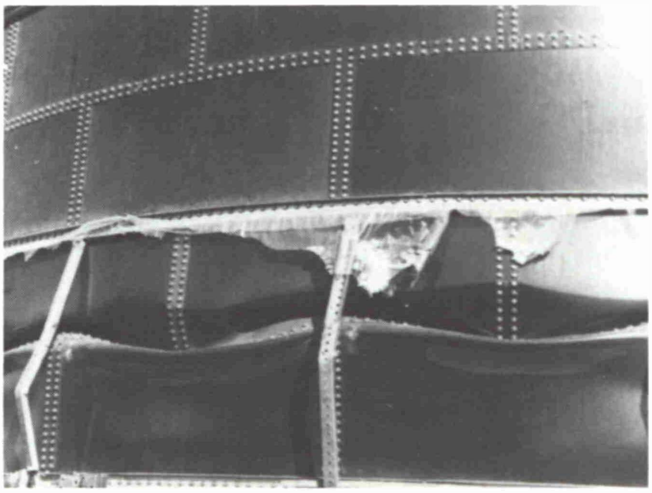

Fig. 46

Fig. 50

Meanwhile, a further series of problems are appearing, such as:

- Deformation due to friction forces. The ensiled material exercises such high pressures on the silo walls that these become deformed in the manner shown in Fig. 46.
- Wind effects, as can be seen in Fig. 47, due to failure to take account of traction effects and installation of appropriate anchorages.
- Explosions. Grain and flour dust is highly explosive under the following conditions:
  1. Granulation less than 200 microns.
  2. Concentration of 50 g/m³.
  3. Source of energy equal to 1 millijoule.
  4. Temperature of over 400 °C.

These conditions are easily reached and it is surprising that there have not been more explosions, since 400 °C can be produced by:

- The spark from friction between metals.
- The operating of a switch in poor condition.
- A cigarette.
- A cutting or soldering tool, etc.

Fig. 48 shows an explosion in an American silo, Fig. 49 an explosion in a silo at Bremen, West Germany, and Fig. 50 an explosion in a Spanish silo.

This concludes a broad and general outline of silo construction and technology over the last one hundred years.

Acknowledgement

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