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New steps towards the knowledge of silos behaviour**

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A b s t r a c t. The structural complexity of silos has been object of interest for engineers and researchers for more than a century. During years, mathematical models have tried to describe the problem with as less simplification as possible. Meanwhile, experimental tests in silos have been conducted in order to simulate reality.

Phenomena are not yet well understood, but researchers have better analysis tools every year. The Spanish research team is now trying to provide some relevant result to the international community of silos researchers.

This is the reason why finite element models are being improved. The filling and discharge phenomena as much as eccentricity influence are simulated to better understanding the silo behaviour. Commercial computer software with high capacities have been chosen to get an accurate simulation of the mechanical behaviour of the bulk solid, the silo wall, the contact between them and the dynamics of the phenomena.

At the same time, difficulties have been found to apply these models due to the lack of knowledge existing about the mechanical parameters of the bulk materials that are required by the theoretical models. So an ambitious set of bulk materials tests have been designed to get such parameters with enough accuracy.

Nowadays the simulation of silo explosions is not one of the research team objectives, however tests include determination of parameters of the bulk material related with the analysis of explosions, which anyway are necessary to a proper design of installations for protection and prevention.

Finally, three experimental silos have been erected. They are cylindrical of 1.9 m in diameter and 5 m in height of the vertical wall, with emptying hoppers designed with three different eccentricities. The wall has been made of smooth steel, with enough thickness and reinforcements to be considered rigid. Specially designed sensors have been fixed in these silos, in order to measure the horizontal pressure and the friction force between the wall and the bulk solid. The horizontal pressure cells measure the deflection of a circular thin plate by means of four strain gauges, and the friction forces sensor measure the deformation of a small cantilever beam by two strain gauges.

Although the research work is now in progress, the first results are hopeful and our research team wish to help in better understanding of these interesting structures.

K e y w o r d s: silo, finite element, strain gauge, material parameters

INTRODUCTION

Silo design has been a concern of scientists and technicians since the end of the 19th century. When it seemed that we were finally beginning to understand the physical phenomena arising from the interactions between grain and the walls of its storage structures, new uncertainties appeared that maintained silos outside of the safety margins associated with other types of building.

The complexity surrounding silo design is mostly due to three factors:

1. The mechanical behaviour of the stored material is complex and poorly understood. This material can be very different, for example, it might be dry grain, grain with a certain amount of moisture, or very dusty material, *etc*. Since these are disaggregated materials, the laws of solid mechanics do not apply. Further, their mobile nature makes it difficult to apply the classic theories of soil mechanics, which focus on disaggregated but static materials.

2. The contention structure usually has a complex shape. Form an all-encompassing point of view, even the most simple silos – cylinders – are usually connected to a conical hopper, or are grouped together in multiple cells. The use of structural elements providing rigidity, corrugated

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walls or elements to assist handling or manoeuvring, do not make design any simpler. Matters become worse if the silo is not circular or if filling or emptying is not symmetrical.

3. The interaction between the grain and silo wall is an important factor. It has always been known as the main factor differentiating silo design from tank design. This interaction is more complicated than at first thought, especially in areas where there is a change of direction or where the walls of the silo are not smooth.

These peculiarities have been discovered progressively, so we need to take a look at the history of silo design if we are to understand the present and map out our hopes for the future.

The main aims of this paper are to present the work that has been performed over the last ten years by the Spanish silo research team, whose centre is at the Polytechnic University of Madrid, to show what the team is up to at the present time, and to explain what it hopes to do in the future. Papers based on this work have been published in both Spanish and international journals, many presentations have been made at different congresses, and several doctoral theses have been completed. This paper is therefore a summary of what this group has achieved, and reports its global vision regarding silo research.

I should first point out that all the members of this group are Agricultural Engineers, and that our interest in silos concerns the storage of agricultural or food products such as grain, flour or forages. I should also make it clear that in Spain, the construction of silos was common during the second half of the 20th century, and that the present storage capacity meets practically all the country's needs. The construction of new silos is aimed mainly at the replacement of those that have become old or unserviceable. However, the special relationship between Spain and certain developing countries means that the best technologies are easily exported to the latter: this is therefore an area of research involving national interests.

Fig. 1. A recent (October 2004) accident in a Spanish silo.

There are also powerful reasons related to worker safety that demand research into silo design should continue: unfortunately serious accidents with loss of life still happen when silos explode or rupture (Fig. 1-13).

A BRIEF HISTORY OF SILO DESIGN

The construction of modern silos began in the second half of the 19th century when grain harvests began to become abundant owing to improvements in agricultural technology. International trade demanded that these products be stored at ports, but the increase in mining and the process of industrialization during that period also led to the need for other silos around the country. Further, the possibility of using the railways to transport grain over long distances demanded new storage facilities to be built.

The first of these 19th century silos were made of wooden planks and had very simple designs. The grain they stored was understood to behave as a liquid, and it was believed that the only vital mechanical property that had to be known was its specific weight.

Soon, the first steps were taken towards understanding the behaviour of stored grain as a soil. The 19th century had seen great advances in soil mechanics and the concepts of internal friction and friction with walls, *etc*. were in common use. The greatest advances in silo design however came from the work of Janssen in 1895: his theory of silo design, which discusses how to calculate pressures in silos, has become generally accepted.

This theory, which has been borne out over more than a century of practical experience, is a very simplified approach to silo design and thus has undergone successive corrections over the years. The original theory describes the friction between a layer of grain and the silo wall and establishes the static two-dimensional mathematical equilibrium of the vertical forces – from which the vertical pressures, and thus the horizontal pressures, can be obtained. Establishing the stresses in these granular solids requires the use of Rankine's simplification. Janssen's theory (1895) showed silos to behave in a manner very different to that believed at the time. Soon, the design of all silos was based on his work.

Of course, for a design to be drawn up, certain properties of the material to be stored have to be known, for example the specific weight, the internal friction angle, and the grain-wall friction angle. Certain geometrical characteristics of the cell, such as the cross section, must also be known.

During the early 20th century, silos all over the world begun to be built from reinforced concrete – a modern, reliable building material. Other materials were also used, however, such as brick or steel, copying the construction technique used in tanks. However, several large accidents fuelled the idea that a definitive version of Janssen's equation was yet to be achieved. In the 1940s, experiments began with small model silos. The pioneers in this were the

Reimbert brothers, well-known civil engineers who had worked on soil mechanics. These engineers highlighted the shortcomings of Janssen's theory and proposed another equation based on similar foundations. The two equations differ slightly with respect to the area of the silo where pressures are maximum, and somewhat more with respect to the areas where these pressures are least, although the final equations are still very similar. However, these authors showed for the first time that horizontal pressure increases during emptying. They were not able to explain the phenomenon, but they did suggest it might have been the cause of several silo accidents. From that moment on, the emptying of silos became a key element in international silo research.

Fig. 2. The accident of the Transcona silo in Canada 1913 (taken from http://www.archiseek.com/).

The Reimbert brothers' equation (1959) existed alongside that of Janssen until the 1970s. At this time, further experiments were performed with both model and real silos in France, Germany and Russia. The idea of these experiments was to fix safety coefficients for emptying. However, Jenike and Johansson (1968), in the USA, were the first to propose theory on overpressures during emptying. According to this theory, pressure build-up is due to a change in the Rankine equilibrium in the grain movement zone, and an overpressure wave in the transition zone between grain in the static and dynamic state. Though widely accepted, the theory of Jenike and Johansson (1968) had little practical effect on silo design due to its complexity.

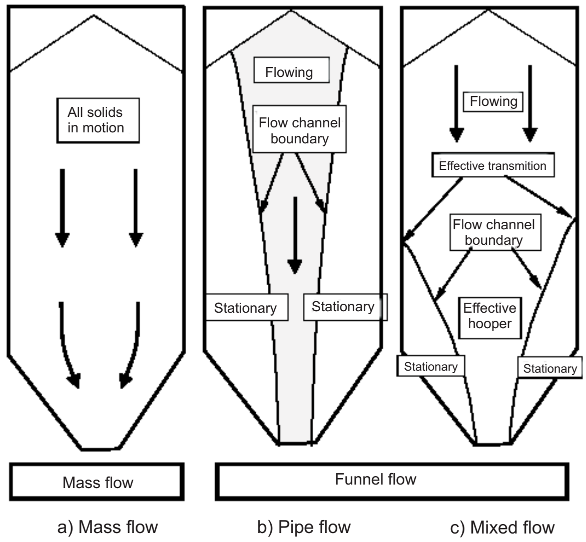

Fig. 3. Types of silo flow (Eurocode 1, part 4).

It was also Jenike and Johansson (1968) who explained the different ways that grain might move during emptying and the different flows that develop. These features also became the subject of research given their huge importance in silo use.

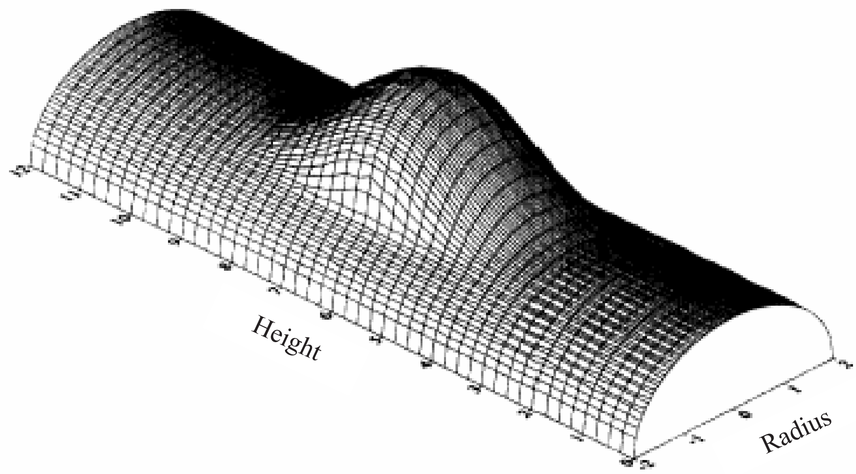

Fig. 4. Finite element simulation of a silo wall (Chen, Rotter and Ooi, 1998).

Several years later, scientific debate broke out between the Reimbert brothers and the Greek researcher Briassoulis (1991), who showed the mathematical weaknesses of the Reimberts' equation. As a result, the brothers' theory began to lose following, and engineers turned back to the Janssen equation.

It was also in the 1970s when the finite elements method was first used in silo research by the Canadian researcher Jofriet *et al.* (1977). This line of work quickly expanded thanks to developments in computer science and the appearance of elaborate, commercial, finite elements programmes. This process allowed researchers to free themselves of the basic hypotheses associated with the classic methods, which were so often too simple. Naturally, the use of these methods soon allowed models of grain behaviour to be developed as well as the development of models for the forms of friction produced between the grain and the silo wall. This widened the field of research to the physical properties of the materials stored. The works performed by Bucklin *et al*. (1996), Thompson and Ross (1983), and Puri (2002), from the USA, were decisive in this area.

The finite elements method also allows the structural behaviour of silo walls to be investigated, as well as with the determination of the grain loads: thus, the space between these areas is bridged. The work of Rotter *et al*. (1998) stands out in this area, although these authors have also worked on many other silo problems.

Very elaborate design procedures thus came into being, involving three dimensions and making use of behaviour models for the materials stored – for example elastic and elasto-plastic behaviour models, although clearly these were used outside their traditional fields. These models also took emptying into account as a transitory phenomenon. Examples of these procedures are that of Eibl and his co-workers (1982) and those of researchers who followed on from his work, such as Rombach (1995).

The use of small scale model silos for examining different effects grew during the 1970s and 1980s. Many interesting papers were produced, such as those by Nielsen (1977). The 1980s also saw very important experiments performed with real silos by Askegaard and Brown, 1995, and later by Munch-Andersen and Nielsen, 1986; Enstad, 1983; Rotter *et al*., 1989; Kmita, 1991, and others.

In the early 1990s, new information on silo emptying phenomena became available. Zhang (1993) proposed considering the dilatancy of the grains in their vertical displacement as a key factor in the development of overpressure (building on an original idea by Smith and Lohnes, 1983), and developed a complete theory on the subject.

During the 1990s, thought turned to the possibility of using discrete elements methods in silo research. Once again, Jofriet's (1997) and Rotter's (1989) teams were pioneers in the field. Using this procedure, grain becomes an individual element with its own movement, allowing emptying and flow to be analysed without so many simplifications. The limitations of computer power means the method still has to be fully developed, but it is hoped that one day it will help solve complex problems such as pressure variations at silo cross-section changes, *etc*.

Other problems have recently been tackled that before were never taken into account, such as the problems caused by vibrations and the sound produced during emptying. The work of Tejchman (1993) and Wensrich (2002) stands out in this area. Another interesting but little explored field is that

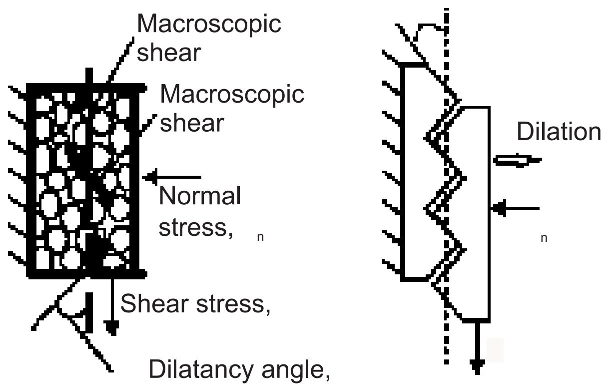

Fig. 5. The dilatancy phenomenon in silos horizontal overpressure during emptying (Zhang and Britton, 2003).

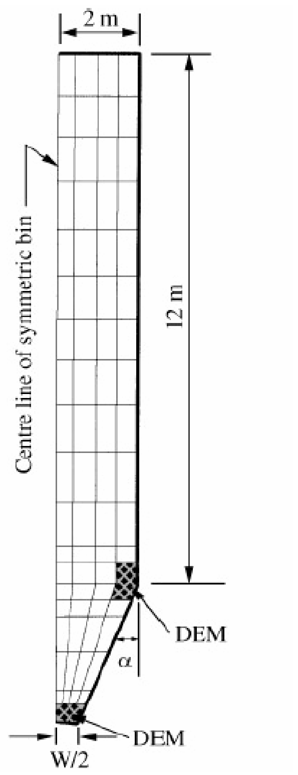

Fig. 6. Hybrid model between finite and discrete element methods (Jofriet *et al*., 1997).

of explosions due to dust. A very large percentage of all silo accidents are due to dust explosions. The work of Eibl *et al.* (1982) in Germany is the most advanced in this area.

REGULATIONS AFFECTING SILO DESIGN

Parallel to the scientific advances made in silo design, different countries and international bodies have produced their own regulations and legislation. Standards and guidelines regulating silo construction are, however, relatively new. The first structural standards were not produced until well into the 20th century, and only in the second half were the first silo design standards introduced (referring to the determination of actions and loads). In the USA the American Concrete Institute (standard ACI-313) and the American Society for Agricultural Engineers (ASAE EP-433) took care of these matters. In France, the first standards were established by the SNBATI and then later by an official standardisation body, the AFNOR. From the outset, the standards for Germany were established under the official DIN system (DIN 1055-6). Many other countries also developed their own standards such as Canada, Russia and Australia. The classic models of Janssen, the Reimbert brothers and others were all used, and restrictions imposed in order to improve safety.

As a result of international collaboration, the ISO standards were published. These are quite similar to the various national standards. The European Union is now trying to adopt a common system of standards for its member countries with respect to structures and construction. This involves the long process of proposing and approving Eurocodes. In Eurocode 1, regarding the calculation of actions in buildings and structures, a specific section (section 4) has been introduced for silos and tanks. In other Eurocodes, such as Eurocode 3 regarding steel structures or Eurocode 8 regarding seismic events, large sections are given over to silos. Currently it is the most complete and up-to-date system of standards that has ever been available. The latest revision of Eurocode 1 section 4, which is near to publication, contains more than 100 pages and covers classes of actions, the testing of storage material properties, and the determination of loads during the filling and emptying of slender, squat and retaining silos. Also taken into account are thermal loads, hopper design, eccentric emptying and explosions. It is, therefore, the benchmark system for the rest of the world.

Nonetheless, not all problems have been solved. For example, there are hardly any indications on the way the finite elements method should be used, or any information on the interaction between adjacent cells.

THE WORK DONE, AND STILL TO BE DONE, BY THE SPANISH RESEARCH TEAM

The Spanish research team began its work in silo engineering and design in 1993. New faces have joined the team over the years, and though initially we were all stationed at the Polytechnic University of Madrid, our members have now moved to universities all over Spain. However, we still work together. To date we have tackled problems related to numerical simulation and have tested the properties of storage materials in the laboratory. At the present time we are about to undertake work with experimental silos and have begun some tests on the ignition of dust.

Finite elements models

When we began to work on the development of numerical models for the design of silos in 1993, there were already a number of teams in other countries that had been working for several years in this area. However, at that time, we were able to take advantage of the power and reliability of commercial computer programmes. Most of the other groups were using in-house programmes which they had been perfecting over the years. These programmes, however, were not optimised for speed or the convergence of results. The available commercial programmes, however, while they could not be easily modified, offered much better calculating power. We decided to follow this route and began to work with the ANSYS program. Our first achievements was the simulation of a two-dimensional silo with a rigid wall and a flat bottom whose pressure curves looked very much like those reported by other research groups.

Encouraged by these first results we began to perform parametric studies with the aim of better understanding the phenomena that occur inside silos and the weaknesses of the simulation method. Results were obtained with different types of meshing, storage material behaviour (elastic and elasto-plastic behaviour), friction model, wall type, and type of bottom etc. (always in a static situation and with the limitations imposed by the programme and computing power). The first results were published in Spanish in 1995 (Ayuga, 1995).

Fig. 7. Silo explosion in France. (taken from Masson 1998).

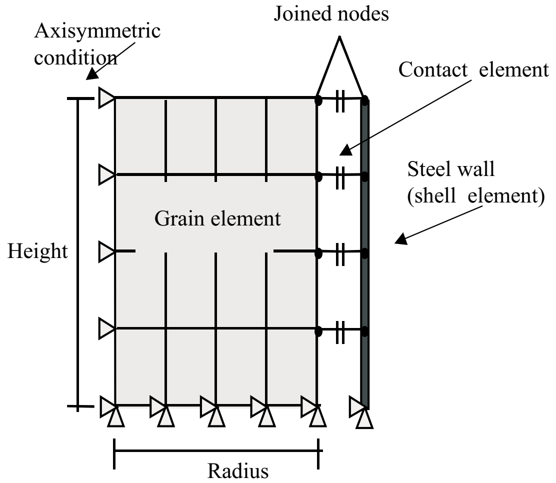

Fig. 8. A simple finite element model to simulate the grain and the wall at the same time.

The next advance was the formulation of emptying of two-dimensional silos. For this, the theory of Jenike and Johansson was taken into account, as well as the dilatancy theory of Smith and Lohnes (1983), Zhang *et al.* (1993). Friction lines were generated within the grain mass that formed an internal funnel over which the grain moved. These lines cut the silo wall at one point where an overpressure was produced. By varying the inclination of these lines, the overpressure wave spoken of by Jenike and Johansson (1968) could be seen, and we were able to trace the envelopment curve to obtain the emptying loads. This was not a real, transitory regime but a static procedure with large deformations. Nonetheless, since the greatest over-pressures are produced in the first moments of emptying, the results appear to be believable. This work was published in 2001. (Ayuga *et al.*, 2001a and Ayuga *et al.*, 2001b).

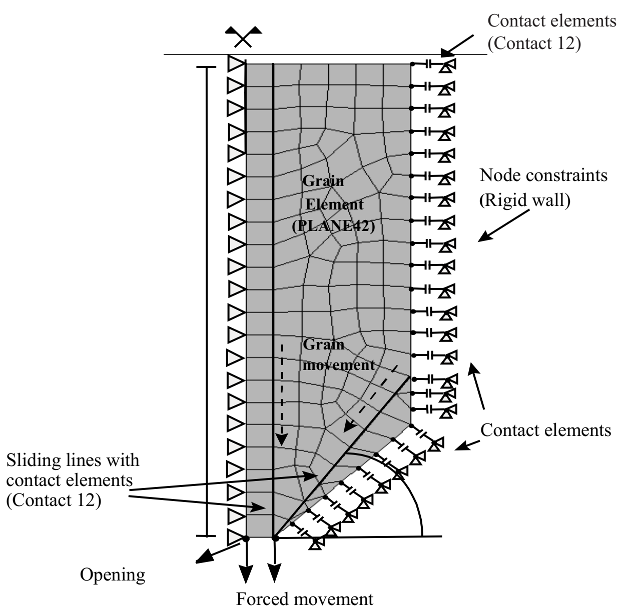

Fig. 9. A finite element model to simulate the silo emptying.

At the same time the team took part in an international project directed by Rotter to compare different studies that had used numerical methods (Rotter *et al.*, 1998). Answers were sent in to a problem posed to many groups regarding the pressure developed during filling at successive layers, and those developed during emptying. This work directed us towards looking into the problem of filling and its simulation.

Using two-dimensional models, three additional problems were investigated: the pressures developed at corrugated steel walls, pressures due to thermal variations, and the buckling of the walls. With respect to the pressures developed on corrugated walls, it was concluded that the finite elements method could not adequately simulate the phenomena that occur. Rather, a procedure was required combining the finite and discrete elements methods, which we were unable to tackle with the computer software available. Interesting results were obtained, however, with respect to the thermal variations and the buckling of the walls. We are currently in the process of having them published.

Over the years in which the two-dimensional models were perfected and the above studies performed, computers had become more powerful and were able to run the newly available, upgraded versions of the commercial ANSYS programme. Three-dimensional models of cylindrical silos were therefore developed, and for the first time we were able to study the influence of emptying eccentricity on static pressures. This movement to three-dimensional models led to a change in grain-wall friction models, which had also been improving. The results obtained with these first models were published by Guaita *et al*. (2003). Using a similar methodology, a three-dimensional silo model with a rectangular cross section was also developed; the results obtained are currently in the process of being published.

The next step in the improvement of silo simulations was the introduction of the transitory regime into these three-dimensional models, making time a variable of the model. This allowed the first moments of emptying to be studied. With this model we have obtained interesting results for circular silos with flat bottoms and eccentric hoppers; these results are also in the process of being published.

Presently, we are working on the eccentric filling of silos by layers and researching into patch loads, using the models currently available.

In the future we foresee the possibility of more accurately modelling the behaviour of the material stored (until now elastic or elasto-plastic models have always been used), and of studying the interaction between adjacent cells and the buckling and thermal actions in non-circular silos. We also hope to start a line of work using the discrete elements method for silo design.

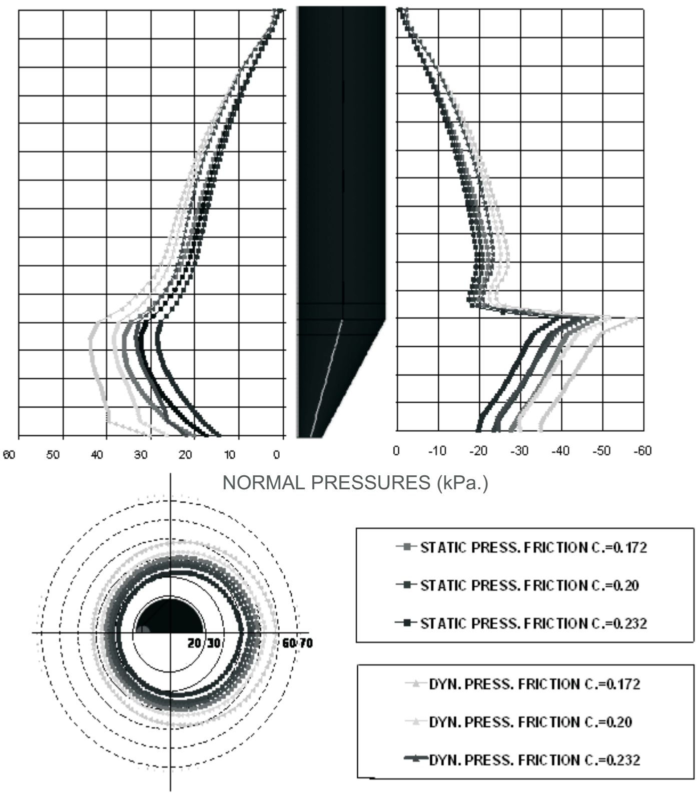

Fig. 10. Influence of the hopper eccentricity on static horizontal pressures.

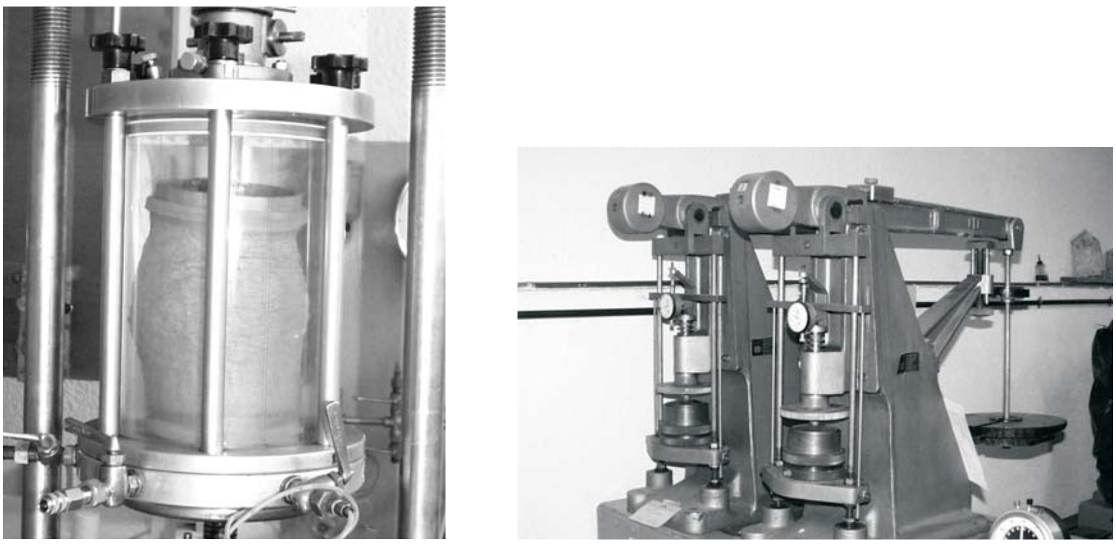

Fig. 11. Triaxial and oedometer tests.

Laboratory tests on granular materials

Since the beginning of research into silo design by numerical methods, there has been insufficient experimental work to determine the mechanical values of the materials actually stored. The generalised use of classical theories for silo design led to some tables on specific weight values being drawn up, as well as some concerning internal friction angles. The cohesion values of some products were also known. Friction with the walls, however, had been less studied, and values such as the Poisson ratio, the modulus of elasticity or the dilatancy angle were practically unknown. These, however, are essential in the numerical design of silos, and many authors had to assume values in order to perform their work.

It was for this reason that our team began a laboratory project to determine these mechanical values. Other groups around the world were also doing the same, working with rather small numbers of storage materials, although with very precise (and very costly) instrumentation. Our aim, however, was different: we wanted to test a great variety of materials using ordinary geotechnique laboratory equipment.

To date we have completed tests on 18 different types of grain (wheat, barley, maize, soybean, sunflower seeds, lentils, *etc*.), four types of flour (wheat, barley, soybean and maize), sugar and powdered sugar. These tests allowed us to determine specific weights for different pressures, apparent cohesions, internal angles of friction with steel and concrete, moduluses of elasticity, Poisson coefficients, dilatancy angles, surface humidities and hygroscopic humidities.

To obtain these values we used a compression press, an oven, and made use of the direct shear test, the oedometer test, and the triaxial test.

Specific weights were determined using a 1 litre Proctor mould, allowing the grain to fall and then compressing it in a press. This allowed us to determine the variation curve for the specific weight with changing pressure. Using a direct shear apparatus we obtained the apparent cohesion of tested materials, the internal friction angle and the dilatancy angle. By modifying a shear box we were also able to determine the friction angle with steel and concrete.

A triaxial apparatus was used to determine apparent cohesion and the internal friction angle – values which were compared to the results obtained with the direct shear test. The Poisson coefficient was determined by impeding the internal deformation of the sample. The use of triaxial apparatus and an oedometer provided the modulus of elasticity of the different materials.

The oven allowed the moisture level of each sample to be determined: many properties can vary with changes in moisture level. However, the influence of this moisture was not studied. The results were partially published by Moya *et al*. in 2002; we are now in the process of publishing the remainder.

We are now developing a procedure to measure the resting angle and we will continue testing different storage materials – certainly more flours, and probably forage materials as well. We also hope to study the variability in measurements more thoroughly, for example, variation in moisture levels, the influence of the tests themselves, or that caused by the actual researchers involved.

It will also be necessary to determine new mechanical properties if any modifications to the behaviour models for use in numerical design are to be made. Hypoplastic models or models in which viscosity is taken into account will probably require new testing be undertaken.

Testing with experimental silos

The experimental confirmation of numerical models is a constant requirement, but few papers have been published in this area.

In 1997, our group made the first attempt to measure the pressures developed in real silos. We were lucky enough to have the cooperation of a seed company who allowed us to install sensors in one of their silos. This silo was in use during the week, but we were allowed to use it for our experiments on the weekends. The silo in question was made of corrugated steel sheet, was circular, was centrally filled and emptied, and was located about 70 km from our laboratory. Two types of sensor were developed. One of these, for measuring horizontal pressure, was a circular steel membrane 10 cm in diameter equipped with four strain gauges on its surface. These were used to measure the deformation of the membrane and to deduce the mean pressure exerted by the grain on the silo wall. The sensor was screwed to the wall of the silo at four different heights. Another sensor was positioned close by to measure friction. This was made from a steel sheet belonging to the wall of the silo itself, which was welded to a cantilever. A strain gauge was then added to the upper and lower faces of the cantilever. The deformation of the cantilever was thus determined and the friction deduced. The cantilever was fixed to a steel structure and anchored to the silo wall.

Fig. 12. Pressure cells in a silo with corrugated walls.

This first attempt to take readings in a real silo was a total failure. The work time window was too small, the filling mechanism was old and had only a small capacity – it took hours to fill the silo – and we had to repeat everything every time we did the tests since the silo was in use during the week. Also, the corrugated wall of the silo was a real problem when trying to fix the sensors in place - we had to fill in the spaces with foam. Neither was the friction sensor as reliable as we had hoped. So, we abandoned trying to borrow silos and looked for some funds with which to buy our own.

Full scale silos are often installed at research centres. Their use means that experimental conditions can be better controlled and the monitoring instrumentation used more complete. However, the cost of their design and construction is high and once installed it is hard to change variables such as their height, diameter or shape, to see how these might influence the results.

Medium sized model silos are therefore commonly used. They are relatively cheap to make, and testing is cheaper too. Further, the variables mentioned a minute ago can be more easily altered. However, the ‘scale effect’ has to be taken into account: changing the dimensions of these structures also changes their behaviour. Finally, small scale model silos are the cheapest, but they also suffer the important drawback of the scale effect, making results difficult to interpret.

Fig. 13. Experimental silos in Madrid. The friction cell and the pressure cell.

We decided to use silos similar to true size but specially designed for research. Three full-scale silos were designed - cylindrical in shape and with conical hoppers of different eccentricity. The silo cylinders were 5 m high and 1.9 m in diameter. The hoppers were 1.9 m high. The total height of each construction was 12 m, not counting the grain raising mechanism. The silo bodies were made of steel with reinforcements at the silo-hopper junction and in the most perforated areas where the sensors were installed.

For the study of normal pressures and friction forces, two types of sensor were designed to be fixed to the silo wall by mobile supports - similar to the sensors used in our first attempt, but now perfected. These sensors are distributed around the circumference of the silo. Four pairs of sensors are separated by 90°. Each pair is composed of one pressure and one friction sensor, separated by a distance of 25 cm. The first two sensor positions are below the silo-hopper junction, while the third is 1.8 m distant. In a silo with a concentric hopper, twelve sensor positions were used to obtain the precise distribution of pressures on the wall.

Extensometric band technology was used in the design of these sensors. Via a Wheatstone bridge with a temperature compensation mechanism, these bands transmit electrical signals induced by the pressures developed in the stored material to a data logger and a PC running appropriate software.

The most important development with respect to the sensors used in our first trial is the change in the anchoring mechanism. This was designed to interfere minimally with measurements. The sensors are now fixed in position using bolts welded to the silo wall.

We hope to begin work with these silos very shortly – perhaps in a few days. At this moment we are calibrating the sensors.

Dust explosions

To assess the risk of a silo explosion (or of the explosion of other solid material storage structures), the conditions in which an explosive atmosphere develops - dust suspension in the air - have to be understood, as well as the circumstances in which ignition can occur. The first step is to determine the basic characteristics of inflammability, explosivity and thermal susceptibility of the material stored, and then to apply this knowledge in explosion prevention and protection mechanisms.

This requires a table of experimentally determined characteristics be drawn up for the different materials stored, so that their behaviour can be computer-modelled and used in design procedures to prevent explosions. The tables that currently exist deal with very few materials.

To date, we have focused on typical agricultural and food products; their characteristics are being determined in a specialised explosives laboratory. The products we are looking at are dust of ground sugar, ground maize, barley, alfalfa and wheat. Our plan is to first determine the characteristics of inflammability, explosivity and thermal susceptibility in these materials and then to select one of these products for more detailed thermal stability studies using an isothermal oven. The idea is to analyse the behaviour of the product with the greatest thermal stability in order to determine whether it undergoes exothermic decomposition during storage – which could lead to auto-combustion.

The variables we have measured are the minimum ignition temperature, the limits of flammability, the minimum ignition energy, the variables of the explosion curve, and those of susceptibility to spontaneous ignition.

We hope to continue testing with more products and then make design proposals for agricultural silos that will reduce the risk of explosions, or minimise damage should they occur. The few studies performed to date are directed towards preventing explosions, but they have not looked into the behaviour of silos when explosions actually occur. Neither has the behaviour of protective measures been studied, nor the influence they may have on silo structure.

In the more distant future, we hope to develop tools based on the finite elements method that should allow the study of explosions. We also hope to look for new explosion prevention and protection systems.

CONCLUSIONS

1. The research performed in the area of silos has been very extensive and covers many disciplines. However, more work remains to be done: new problems need to be tackled and older ones need to be analysed with less simplified methods.

2. Silo design standards and regulations are slowly incorporating the progress made in order to improve the safety and reliability of these structures.

3. Our research team has made important contributions on finite elements models for silo design and the determination of the mechanical values of materials. At this time we are working in both these fields as well as examining the pressures developed in real silos and determining the variables associated with explosivity.

4. The prospects for the future are good: we hope to be able to deepen our knowledge in these areas and to begin work in others.

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