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From Silo Phenomena to Load Models

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ABSTRACT: With special focus on work done by J. Michael Rotter and the Author, this paper aims at presenting the duality between complexity and simplicity in relation to silo phenomena and specification of loads for silos. The presentation takes its starting point in complexity - a description of phenomena which may play a significant role in developing the loads in a specific silo and which therefore must be understood if a proper design shall be made. The paper then turns to simplicity – the transformation of this complexity into simple, safe load models as prescribed by standards. It is stated that the present rules in some cases implies a considerable loss in economy and in other cases may compromise the intended safety level. Therefore the overall conclusion is that there is still a need for silo research and for a transfer of new knowledge into engineering applications.

1 INTRODUCTION

Silos are fascinating research objects. Not only is the physical behaviour of the stored materials - being many types of particles - more complex than most other materials, but also the structures themselves – many of them being shell structures – are among the most demanding structures, seen from a design point of view. Furthermore, the requirements for experimental techniques leading to accurate results are higher than for most other research objects within structural engineering.

A single word characterizing silo phenomena is complexity.

Structural engineers have to deal with this complexity in their daily business in designing safe silos, and as part of that be able to evaluate the influence from different requirements to working conditions for the silo, whether it is in a long term storage facility or a buffer as part of a factory production line. This is where standards with their simplified rules are helpful in giving relevant guidelines for the design. Standards may therefore be seen as the result of a transformation of scientific principles into engineering applications. They must be fairly easy to understand, with a limited set of parameters to deal with, based on documented knowledge, and specify rules which lead to a safe design of structures.

A single word characterizing the aim of standardization is simplicity.

The transformation of scientific principles into engineering applications thus has to deal with the duality between complexity and simplicity as described above. Few, if any, has been as competent as J. Michael Rotter in handling this duality around the two subjects *buckling of shells* and *loads in silos*. The author to this paper has not been involved in scientific studies of buckling so only *loads in silos* will be dealt with in detail in the following.

The author has had the fortune to collaborate through many years with J. Michael Rotter on the study and specification of loads in silos. The collaboration began in 1983. J. Michael Rotter was at that time working at University of Sydney and had developed an interest in shell buckling. He had realized how big a challenge it was to understand buckling in silos (Rotter 1983, Jumikis et al. 1983 and Ansourian et al. 1983). The Author had from a general interest in experimental mechanics developed an interest in accurate determination of pressures in silos (Askegaard et al. 1971). In 1983 he could present results which indicated severe non-symmetric loads in notionally symmetric silos (Nielsen 1983).

Based on the fact that non-symmetrical load patterns have a major influence on buckling, this became the starting point of a scientific cooperation which took both of us through discussions on different silo phenomena into a collaboration concerning international standardization concerning loads in silos (ISO, CEN-EUROCODE). It also involved participation in a European research collaboration, CA-Silo (Brown & Nielsen 1998).

The author is highly indebted to J. Michael Rotter for stimulating discussions throughout all those years.

With special focus on work done by J. Michael Rotter and the author, this paper aims at presenting the duality between complexity and simplicity in relation to silo phenomena and specification of load models for silos.

2 COMPLEXITY - SILO PHENOMENA

The following presentation of silo phenomena with reference to the specification of loads in silos takes its starting point in a description of the history of a particle that passes through a silo.

2.1 *The history of a particle*

A look at the history of a particle which passes through a silo reveals several phenomena (Nielsen 1998) which may all play a significant role in developing the loads in a specific silo and which therefore must be understood if a proper design shall be achieved:

- The bulk handling equipment at the inlet of the silo leaves the particle to be filled into the silo with a certain direction and speed, which, in interaction with other falling particles and the air resistance, determine the trajectory of the *falling particle*.
- After a possible *impact* with the wall, the particle impacts on stationary particles at the surface of the stored material, after which it may *bounce or slide* down the surface, or, in case of a powder particle, *float in suspension* on the surface, until it finally finds its position as a member of the *stacked particle assembly*. It is important to notice that this process forms the stack of the particles, and dependent on the shape of the inlet, the particle size, the distribution of the particle sizes, and on the shape and surface roughness of the individual particles, the stored material may end up in being a inhomogeneous and anisotropic, denser or looser stored material (Nielsen 1983, 1998).
- As filling of the silo continues, the embedded particle participates in a *consolidation* associated with the *development of strength* of the stored material. The consolidation may be associated with the development of an *interstitial air pressure.*
- During the consolidation process the *contact forces* between the particle and its neighbours may be rearranged, especially in regions with relatively high shear forces.
- After the filling has stopped the rearrangement of the contact forces between the particles continues due to interstitial air flow and creep in the particles
- At the onset of flow, possibly assisted by air induced near the outlet, a dramatic rearrangement of contact forces takes place, and at a certain time the particle normally will start move and follow a trajectory. It may pass zones where it is in close contact to its neighbouring particles (rigid body movement) or zones with rapid reorganization of contact forces (shear zones or shear planes). It is important to note that the effective stiffness of the stored material at this stage may vary between being relatively high (elastic state) and zero, being zero in zones where plasticity is fully developed and where the flow is similar to the flow of liquids. Zones with flowing particles are illustrated by so called flow patterns. Especially two flow patterns are important for this discussion. One is *Pipe Flow* where the moving particles form a pipe above the inlet in a way that the particles at the surface will be the first to get out of the silo. The other is *Mass Flow*, where all particles move during discharge, but where the cylindrical part of the silo contains an elastic (rigid) body moving downwards. Where such rigid zones are moving in contact with the wall any irregularity of the silo wall forms an obstacle that changes the load distribution in the silo (Askegaard et al. 1971). While discharge normally takes place as a quasi-static phenomenon where dynamic forces play an insignificant role for the development of loads on the silo wall, it may happen that very serous impact loads are developed. The reason for that is normally an internal collapse of rigid parts of stored material formed above or around flowing zones which, as discharge progresses, reduces its support of the rigid zones (Nielsen 1984a).
- Finally the particle approaches the outlet, contact forces are released, and the particle drops down into the bulk handling equipment.

On this background some items are selected for further discussion with reference to the transformation of scientific results into simplified load models for practical design of silos:

- Continuum versus discrete particle approach
- Load perspectives in steel versus concrete silos
- Experiments – pressure cells versus wall strain measurements
- Experiments – model versus full scale
- Pressure redistribution during discharge

2.2 *Continuum versus discrete particle approach*

Seen in the light of the history of a particle, a *discrete particles* approach would be the natural choice to a theoretical description of the physical behaviour of stored particulate materials. Only a discrete particle approach can end up in a model for the creation of the stack of particles in a silo, and only with a discrete particle approach is it possible to consider the effect of particle contact forces on the silo structure which may be necessary for a structure containing very big particles. Finally, the size of the particles of the stored material has been found to cause a *silo size effect* on loads in silos with rough walls and Mass Flow (Munch-Andersen 1986; Munch-Andersen & Nielsen 1986). The reason is that a rupture plane, as typically formed in dense stored materials, has a thickness of a specific number of particles. This means that the volumetric expansion associated with shearing in the boundary layer between the rigid cylindrical part of the stored material and the wall gives rise to different horizontal strains in silos with different diameters and therefore different pressure regimes.

However, so far the discrete particle approach has not produced realistic results except for very special cases (Chen et al. 1998a, Holst et al. 1999b). The limitations for this approach seem primarily to arrive from difficulties in handling the number degrees of freedom in the stack of particles, first of all the number of particles, of parameters to describe a realistic shape of each particle (wheat grains or a sand particles), of the spatial orientation in the stack of stored material, and of the positions of contact points between the particles. Furthermore, the orientation of the particles and the positions of contact points vary with time, especially during discharge.

Therefore discrete particle approaches have so far mainly be seen as research tools.

In spite of their shortcomings, *continuum* based theoretical approaches therefore seem to be the best choice for practical results. Among those are the classical theories of elasticity, plasticity, etc.

The continuum assumption normally implies that the stored material just after filling is taken as the starting point. As described above this continuum may be inhomogeneous as well as anisotropic which again means that closed solutions are only available in few cases.

Finite element simulations based on continuum approaches have therefore been developed as a tool for practical design.

One of the great challenges in this approach is to find a realistic set of constitutive equations which can still be dealt with in the numerical analyses (Nielsen & Weidner 1998).

Although promising, finite element simulations, based on continuum approaches, still show limited ability to give realistic results (Chen et al. 1998a, Holst et al. 1999a).

Recently, a validated model for filling pressures in square vertical walled metal silos has been published (Goodey et al. 2006). The flexibility of the silo walls makes the load-structure interaction significant in this case, which together with complex constitutive laws for the stored material means that accurate simple models are not available. To the extent that the filling condition is the most serious loading case this is an example of finite element models being able to support practical design.

The considerations related to a continuum versus a discrete particle approach appear also in relation to experimental studies based on model laws, se section 2.5.

2.3 *Load perspectives in steel versus concrete silos*

Load perspectives are very different when seen from a concrete silos point of view or from a steel silos point of view (Rotter et al. 1986).

When *concrete silos* are not too large the design challenge mainly is to ensure an adequate horizontal reinforcement in order to resist the maximum horizontal pressure from the stored material. Non-symmetrical components of loads are of interest in relation to ensuring a sufficient bending strength of the wall.

Thus, for concrete silos the main questions of concern are how big may the horizontal load be, and to which extent is it associated to bending moments in the walls?

In *steel silos* the design challenges mainly are to ensure a proper development of membrane forces and to avoid local buckling of the shell structure due to (vertical) compression (Rotter 1983; 2006; Song et al. 2004). Large horizontal pressures support the structure and make it stronger. Non-symmetrical components of loads are of interest in relation to evaluating their additional contribution to the compression membrane forces which may lead to buckling.

Thus, for steel structures the questions of concern are which magnitude of the horizontal pressure can, on the safe side, be assumed to be present in combination with the critical compression stress in the wall, and which load pattern creates the critical compression stress (Gillie & Rotter 2002).

2.4 *Experiments – pressure cells versus wall strain measurements*

There are basically two ways to measure loads on silo walls, a direct measurement of wall pressure, using pressure cells, and an indirect, using strain gauges to measure the load effect as strains in the wall.

Accurate measurements with *pressure cells* are only possible with an installation of cells which are stiff enough to avoid a local pressure relaxation and which are mounted flush with the wall so that no local imperfection disturbs the pressure distribution when the stored materials moves along the wall (Askegaard et al. 1971; Askegaard & Nielsen 1977).

In concrete silos it is relatively easy to fulfil these requirements because the pressure cells can be built into the wall (Askegaard & Nielsen 1986).

In principle the readings of a pressure cell only represent the area of its active surface. Furthermore, it has been revealed that very big pressure gradients may appear during discharge (Rotter et al. 1986). Therefore many pressure cells may be necessary and readings from wall strain measurements may be used to support the interpretation concerning loads on the silo wall.

The pressure cell technology is more difficult to apply in steel silos. Furthermore, steel silos are subject to higher wall strains than concrete silos, and the strains are therefore easier to measure accurately.

The challenge for using *strain measurements* as a basis for load assessment has been the interpretation, because it is difficult to determine details in the load patterns from measured strains, especially in shell structures.

A procedure of inferring circular silo wall pressures from wall strain measurements has been developed by Chen et al. (1996; 1998b). For thin plate structures, this method is claimed to offer a cheaper determination of load patters than based on pressure cell measurements. The method has the advantage that those local pressure fluctuations which are insignificant to the structural response are automatically filtered out. Furthermore, the outcome is easier to transform to simple yet realistic load models for practical use, because the measured strain is more relevant to different design situations, buckling being one (Chen et al. 1998b).

2.5 *Experiments – model versus full scale*

Phenomena related to real silos have mainly been discovered and studied experimentally. By the interpretation of experimental results it is important to know to which extent a test in a silo does represent tests in similar silos of other sizes. Or more precise: Which are the test requirements that allow for a transfer of results according to a scale law in a way that the scale errors are negligible? A set of test requirements and the corresponding set of scale laws are called a *model law*.

Nielsen (1977) has for various conditions described different types of model laws with reference to silos. The study considers a continuum as well as a single particle approach and it discusses the influence of interstitial air flow on the model law. Among the test requirements are also discussed the use of an artificial field of gravity – centrifuge testing.

The study shows that *scale errors* shall in general be expected. The challenges of modelling have been discussed (Nielsen 1998) for coarse grained stored materials as well as powders and for three scales of silos: full scale, a laboratory scale, 1:10, and a centrifuge model, scale 1:100. The conclusion is that different silo phenomena call for different model approaches, and that the magnitude of scale errors in many cases is not known (Nielsen 1984b).

Any interpretation that involves statements valid for similar silos of other sizes must therefore be carefully argued. This also means that full scale experiments are of special interest.

Most experiments have been carried out in laboratory scale models or small full scale silos, in most cases without a proper reference to model laws. The simple approach has been to compare experimentally determined loads with theoretical results for the pressure distribution – typically Janssens theory (Janssen 1895). By doing so, all assumptions on which Janssens theory is based, one being the continuum approach, are automatically built into the interpretation.

2.6 *Pressure redistribution during discharge*

Everybody having performed tests in silos has observed variations and *oscillations* in the pressure readings.

During filling, the pressure gradually develops until the silo is full.

At the start of discharge is often seen a significant change in pressure level and, especially with pressure cell measurements, it is followed by large oscillations. As discharge develops, redistributions of significant magnitudes may occur with larger pressures appearing first at one place and later at other places (Nielsen & Andersen 1981, Hartlèn et al. 1984).

This means that, while, in a symmetric structure, a symmetric pressure distribution may be found as an average over time, there may be periods with significant *non-symmetrical load distributions*. It also means that, especially in dealing with pressure cell measurements, it is tempting to look at time average to get rid of insignificant local fluctuations. However, that must be done with caution because significant non-symmetric load patterns may disappear.

Altogether this means that in some silos many, very different, load distributions occur from time to time, especially during discharge.

However, most classical theories only offer one pressure distribution for filling and / or one for discharge.

3 SIMPLICITY – SPECIFICATION OF LOADS

In practical silo design it would be very uneconomical to ask each designer to handle the complexity as described above.

The task for code-writers is therefore to transform this complexity into simple, safe load models.

In Europe a main line of the development of *load specifications* may be drawn from the German code, DIN 1055, via ISO/TC98/SC3/WG5 to the present

CEN standard, EN 1991-4 (EUROCODE 1 – actions on structures, Part 4: Silos and tanks) (Nielsen et al. 1992).

The process of load specification involves assessment and simplification of many different types of silo phenomena which are not all fully understood. Some of the important items to be dealt with are the following:

- General principles in load specification
- Deterministic versus stochastic treatment of loads in silos
- Variability of structures
- Variability of stored material
- Design for flow versus design for strength
- Theoretical versus empiric rules

3.1 *General principles in load specification*

The principles in load specification have historically been different from country to country. However, it is always so, that there is an intended *safety margin* between the effects on a structure from a few specified loads, and the corresponding strength of the structure, if correctly designed and build.

The idea is then that the specified loads represent the real loads in a way that the *load effects* on the structure are bigger than the effects from all real loads.

Over time, the philosophy concerning the relation between the specification of the safety margin and load specification has changed. DIN 1055 was, as most standards of that time, based on a deterministic approach, where the load was specified a little on the safe side with reference to an assumed critical load effect. The safety margin was then mainly obtained by a reduction of the strength of the construction material to something named permissible stresses. In this way load models as well as the strength of structures are considered deterministic parameters in structural design.

In specifying the load a little on the safe side it was assumed that this should be a high horizontal load, more or less covering the envelope of maximal pressures as they might appear on the wall during the discharge period. The tool to arrive at such a load was to manipulate the physical parameters for the stored materials. By doing so a considerable part of the scientific justification got lost. First of all the bending moments in the wall were underestimated (Nielsen & Andersen 1981) and the horizontal support to wall parts subject to buckling was overestimated. Furthermore, the load model was not adequate for estimating the critical buckling stresses in silo walls.

As already discussed above, the critical load effects may be very different in concrete and steel silos (Rotter et al. 1986). In concrete silos the critical load effects normally are bending moments and tension in the wall while in cylindrical steel silos the critical load effect normally is buckling of the wall. Safety against tension failure calls for a big horizontal load while safety against buckling call for a load model which produces large vertical stresses in the wall and a small horizontal pressure to support it.

A criticism for a too strong orientation towards concrete silos in the DIN was therefore one of the main points in Rotter et al. (1986).

The present EUROCODE, EN 1991-4, is based on a philosophy where loads as well as strength parameters for the structure are considered stochastic variables with a mean value (most likely) and a stochastic deviation. Characteristic values of loads and strengths are then formed by a mean value plus or minus (as relevant) a proportion of the stochastic part in a way that the probability of exceeding the characteristic value is kept at a given low value. The safety margin is then achieved by the application of different partial coefficients on loads and strength parameters, dependent on the type of load and the construction material.

In this way it is easier to maintain the scientific basis for the specified loads as well as the general principle of structure independent specification of loads.

By choosing one set of high or low characteristic values, as appropriate, for the stored material parameters, it is possible to arrive at a high value for the wall pressure to be used for the specification of reinforcing steel bars in a concrete wall, and with another set of characteristic values to get a safe (low) value of the horizontal load to be used in the design as the magnitude of the support to a wall part subject to buckling.

3.2 *Deterministic versus stochastic treatment of loads in silos*

Even if great effort is put into repeating all details concerning stored material, filling method, discharge rate, etc., results from two tests often show considerable differences in the way in which the pressure develops, especially during discharge (Pham et al. 1986).

This means that although we strive at accurate deterministic descriptions of silo phenomena, loads in silos must to some extent be considered a stochastic phenomenon with a certain probability of deviating with a specific magnitude from a mean value.

In some cases it is even so that a phenomenon is recognised to have a deterministic influence on the load, but, in relation to the structural impact, it is considered too complicated to include a description in the load model, so, for simplicity, the influence of that phenomenon is considered part of the stochastic deviation. The silo size effect (Munch-Andersen & Nielsen 1986) may be seen as an example.

By doing so, the scatter of the stochastic part becomes bigger. As a consequence the characteristic loads as specified in standards will become more extreme, leading to a more uneconomical design than if a better scientific background was available.

Finally, some phenomena have, at the design stage, to be considered stochastic although the corresponding load component in a given case is deterministic. One example is geometrical imperfections which may cause pressure redistributions during discharge (Askegaard et al. 1971). However, the size and position of such imperfections are not known until after construction.

From the discussion above it can be summarised that in the development of load models three contributions to *stochastic deviations* from a mean value shall be considered:

- Observed deviations which cannot be explained
- Minor deterministic influences which are considered too complicated to become included in the rules
- Deterministic influences from parameters which are not known at the time of design or kept open for flexibility in running conditions

It also follows that *more economical designs* can be achieved if the stochastic part can be kept low. This can be done by including more phenomena in the deterministic part – a more complicated design – or by better control of the construction – smaller imperfections in the wall geometry.

3.3 *Variability of structures*

Load models are intended to be valid for as many types of silos as possible. In the following is presented some of the considerations behind the prescription of load models for *different types of silos*.

- Silo size
  The diameter of a silo may vary from less than a meter to more than 50 m. This has two implications. One is that there, as discussed above, might be a size effect on the phenomena taking place in the silos. As stated above that effect is treated as part of the stochastic variation. The other implication is that there is a big difference in the economical balance between effort put into better load assessment and savings on the costs of the structure. EUROCODE has therefore introduced three load assessment classes with the highest degree og simplification for the smallest silos.
- Height to diameter ratio
  In silos with small height to diameter ratios, the silo effect is insignificant and load models based on theories for retaining walls are more realistic.
- Shape of cross sections
  Seen from a theoretical point of view a circular cross section is in many ways optimal and easy to deal with. However, in practise many other shapes are used, such as rectangular or star cells. It is important that load models also cover these silos, which puts severe restrictions on the theories available to be used as the starting point for load models.
- Eccentricities of inlet and outlet
  Non-symmetrical load patterns are more critical than symmetrical load patterns. Even in notional rotationally symmetric silos a stochastic non-symmetric load component is to be expected. However, the non-symmetrical component increases significantly if inlet or outlet is placed eccentric. Especially, for large circular silos with eccentric inlet or outlet it is important that the load assessment is realistic. The redistribution of pressure during discharge in silos with eccentric discharge depends on the shape of the flowing material which so far cannot be predicted reliably (Munch-Andersen & Nielsen 1990, Chen et al. 2006). Therefore the design must be robust for all possible flow patterns. In the EUROCODE three representative shapes are prescribed.
- Inserts
  Inserts are built into silos mainly in order to promote flow. They change the flow regime and thus the pressure distribution. Very little is known in general about the pressure condition in such silos and standards do normally not give rules for loads in such silos. This is an area for finite element calculations and experimental verifications.
- Flexible / non-flexible walls
  Flexible walls give rise to pressure redistributions in a way that decease the loads on wall parts that move away and increase the loads on other wall parts. This is an example of structure-load interaction. Such interaction makes in general load specification complicated and detailed rules are normally not given in standards. For silos with rectangular cross sections the problem has been studied in details (Goodey et al. 2006).
- Internal ties
  Silos with internal ties are even more difficult to deal with than silos with flexible walls. The ties themselves are subject to loads from the flowing stored material, and the tension forces in the ties as well as the local loads on the walls, depend on the curvature of the loaded tie and the movement of the wall as a balance between a pull by the tie, and a push by the load. Load specifications for such silos are limited to types of silos where documentation for proper performance is available, and has so far not been considered mature for standardisation.

3.4 *Variability of stored material*

In silo design, physical parameters play a role, as well on the structure side as on the load side. These parameters are always subject to some variation.

On the structures side there is a long tradition for handling this, and it is well known that the variation of the modulus of elasticity for steel is small, while the strength of concrete varies considerably due to less control of the aggregates and the production process.

On the loading side it is more complicated, and not until the introduction of the EUROCODE a rigorous treatment of this subject has been introduced.

Physical parameters for the stored material are used in the load models. Because structural safety considerations were previously directly combined with the specification of the material parameters to be use, these parameters did not necessarily represent real behaviour, which made it almost impossible to use the standard for stored materials not mentioned in the standard.

Nielsen & Colymbas (1988) proposed the use of well defined *test methods* to determine *stored material properties* for load specification in standards, and Rotter et al. (1998) described how the characterisation of the physical parameters of a stored material may be done.

For simplicity the present version of EUROCODE prescribes for each material one value (best estimate or average) for each parameter (continuum approach). Besides that, a rule is given to calculate *upper and lower characteristic values* for each parameter in order to cope with systematic and stochastic deviations.

By using upper and lower characteristic values for the stored material parameters and by combining those in an adequate way in the rules for load calculation, upper and lower characteristic values of loads come out. The critical loads may be used by the designer as appropriate in the actual design situation.

The variability of the stored materials depends on several factors:

- Working conditions

  A process silo in a chemical production line may during its lifetime receive only one type of material, very well defined with controlled water content etc, while a storage silo at a harbour facility may receive many different materials.
- Method of filling

  For coarse grained particles, different ways of filling may cause different patterns of anisotropy and inhomogeneity (Nielsen 1983), which for simplicity are dealt with as variability.
- Pressure level

  The values of physical parameters of the stored material depend to some extend on the pressure level. In general this is dealt with as variability.

  However, for materials which are subject to developing a high level of cohesion, the stress history has a major impact on the strength of the stored material at a certain time.

  The strength of the stored material is so important for the magnitude of the pressure redistribution during discharge that general load models for silos with very cohesive stored materials are not given in standards.
- Powders

  Fine grained materials in silos may contain interstitial air in a way that the effective stresses in the particulate material disappear and the stored material acts like a fluid which has to be considered an additional loading case.

3.5 *Design for flow versus design for strength*

Many silos are built as part of a process line where the *flow behaviour* is the essential design criteria. These silos are typically designed to become Mass Flow silos. Special expertise has been developed for this purpose with procedures dedicated to test stored materials for the ability to flow and with design criteria for outlet diameter and hopper shape, see various sections in Brown & Nielsen (1998).

The parameters determined this way cannot in general be used for load assessments, mainly because they are determined at a low pressure level (near outlet in a steep cone) while load assessment calls for parameters determined at the maximum pressure level in the actual silo (Nielsen & Kolymbas 1988).

3.6 *Theoretical versus empiric rules*

As far as possible it is preferable to maintain a theoretical background for load specification. In the case of silos there exists one general applicable theory valid for filling of a cylindrical silo, *Janssen´s theory* (Janssen 1895).

When it comes to discharge, a similar simple, universal theory is not available. DIN 1055 did use the same formulas, but, as described above, changed the stored material parameters in a way that produced a higher discharge pressure. The parameters hereby lost their relation to physics, and the rules may be considered empirical in the sense that they reflect something intended in a specific perspective, this perspective clearly being concrete silos.

Nielsen & Andersen (1981) and Hartlén et al. (1984) described a series of observed features in relation to discharge pressures which were not represented realistically by the given rules which just increased the horizontal load but maintained symmetry in symmetric silos. The most important observation was the existence of many different instantaneous local loads which makes it difficult to choose the representative critical loading case.

It was proposed to avoid the manipulation with the discharge load and instead introduce a *patch load* which shall be carried in the most critical position for the structure.

However, for shell structures the structural response to patch loads is not simple to derive from a given load pattern. Gillie & Rotter (2002) have done a parametric study which may serve as guidance in choosing the design patch loads for thin-walled steel silos.

The magnitude of the patch load as introduced in the EUROCODES has been prescribed on an empirical basis. It serves two purposes. One is to have a load which ensures a certain *structural robustness* for not evenly distributed load. The other is to substitute for a proper theory for discharge pressures.

In both cases the patch load shall be seen as a redistribution of the filling pressure and thus dependent on the potential for stress redistribution in the stored material. The *redistribution potential* may be seen as relation between the active and passive pressure at a given pressure level, i.e. the stronger the material the bigger the redistribution potential (Nielsen and Andersen 1981).

The present EUROCODE has introduced a patch load of a magnitude which increases with increasing strength.

Impact, as seen in some silos, has so far been considered too difficult for simplified rules in the standard. Therefore, silos for the most difficult materials are not covered. Difficult materials are those which may develop a great strength during the process in the silo and thus be able to create a considerable resistance to be broken down in the discharge process. These materials with extreme redistribution potentials are characterised by a high internal angle of friction and an extreme ability to develop cohesion, such as cement clinker and soya flour.

The *hopper pressures* were in DIN 1055 purely empirically based. In the EUROCODE the corresponding loads are based on the theory of Walker (1966) which maintains equilibrium and thereby makes the structural design more consistent.

4 CONCLUDING REMARKS

Considering the complexity of silo phenomena it is a continuous challenge to develop simple and economic feasible load models for standards.

The present rules shall be seen as only rough estimates to real loads in silos, with a level of simplification which in some cases implies a considerable loss in economy and in other cases may compromise the intended safety level. Furthermore, the present level of simplicity has only been achieved by excluding difficult cases, i.e. certain silo shapes and certain stored materials.

Therefore, designers are advised to maintain a substantial background knowledge about silo phenomena and use the standards with caution.

The overall conclusion is that there is still a big need for silo research and for a transfer of new knowledge into engineering applications.

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