A Review of CA-Silo: Concerted Action for Silo Research

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Abstract

The origins of a collaborative project on silo research (CA-Silo) are given, along with some of the background case for support. The activities described include contributions on a state of the art in silo research, and brief descriptions on some collaborative research work that was carried out. The ways in which industry was involved with CA-Silo are explained. Research requirements are identified in terms of both general objectives, and short-term requirements for pre-normative research. Finally, some of the project management issues are raised, and the project outcomes are described.

1. Introduction

This paper describes the origins, activities and outcomes of a co-ordination activity that was funded under the auspices of the European Community's BRITE/EuRam research programme. CA-Silo was the acronym adopted for a Concerted Action into Silo Research. It commenced in 1992, and was completed in 1997. The total project budget was 370 kECU (£300,000 approx.)

The silo business is technically complex. In spite of this, relatively few researchers are active in the field. Silo technology is used in many industrial sectors, and expertise lies within a number of different disciplines. Knowledge therefore tends to be diffuse, and research work replicated. The CA-Silo programme was established to bring together the current research in Europe and to form a network of researchers willing and able to collaborate so that future activity would be better informed and a more co-ordinated inter-disciplinary approach possible.

This paper is structured to:
• briefly outline some of the key problems in silo technology,
• explain how and why CA-Silo was conceived,
• describe the activities undertaken as part of the project,
• give the authors' perspective on the importance and relevance of these activities,
• present the achievements of the project,
• describe some of the lessons learned from running such a project, and finally,
• outline the challenges for future research work.

This paper intends to give an outline of work that has been carried out, and why it was carried out. The reader is referred to Ref. 1 in which extensive technical information and references are given. Further technical information on the collaborative projects can be obtained from the contacts named ($\S$12).

2. The Importance of Silo Research

Silos store materials ranging from fine powders to quarried rocks—all worth many million ECU. The cost of the stored material frequently exceeds the cost of the silo. Silo users range from industrial giants to numerous small and medium-sized enterprises.

Silo problems occur in many industrial sectors. In agriculture the storage of harvested produce is important, while in the mining industry there is the need to store mined material or a by-product after separation. The chemical and petro-chemical industries use such structures, as does the pharmaceutical industry where large volumes of product storage may be less important than quality and process control.

Information about silo failures is scarce and somewhat difficult to obtain. Operators and designers are often reluctant to reveal details of "their" failures.

Silo failures can be broadly classified as either structural failure or flow failure. Occasionally structural failures are gross and dramatic, and unfortunately may lead to loss of life. In such cases data may become available through official inquiries, but there are many other cases with less dramatic damage or unacceptable operating conditions which are less well publicised.

Human safety is the primary concern arising from structural failures of silos, but failures can often result in considerable loss of income. In the most extreme
cases structural failure may result in heaps of spilled
material and piles of twisted metal or concrete rubble.
However, the structural failure will often take more
subtle forms, where defects such as local buckling in
a metal silo or splitting and cracking in a reinforced-
concrete silo will make the structure unsafe for use or
unserviceable.

Flow failure is less visual but may lead to equally
dramatic consequences, particularly if remedial efforts
are ill judged. Many injuries are reputed to occur as a
result of ill-considered efforts to make material flow
from a silo. The loss of flow may completely disrupt a
mixing or chemical process, resulting in waste mater-
ial rather than usable product – often with consider-
able economic consequences. Reasons for loss of flow
are various. Among the less complicated phenomena
are arching (where the stored material forms a self-
supporting area within the material, thus preventing
flow through an apparently clear orifice) and ratholing
(where a clear pipe of material from top to bottom
of the silo is emptied from the silo, again leaving
blocks of stationary material within the silo). Such
stationary material – from whatever cause – is prone
to collapse suddenly and such collapses may have
fatal consequences. This is just one example of how
flow and structural failures may be linked.

Many of the fundamental load and flow phenomena
in silos are very complicated and still poorly under-
stood. Silos therefore suffer a disproportionately large
number of structural failures compared with many
other forms of construction. Silos continue to fail, even
though the designers and operators may be working
within available guidelines and accepted best practice.
Designs that appear to have been effective within
their previous design experience may turn out to be
inappropriate; furthermore, silos that have been in
good operational condition for many years can sud-
denly develop severe problems. The lack of appro-
priate and accurate design guidance is therefore clearly
detrimental to silo users.

Many of the technical problems are not easily
resolved. Numerical and experimental tools are used
to study the phenomena involved. Analysts are striv-
ing to generate more accurate models for the predic-
tion of pressures and flow in complex silo geometries
and under complex flow regimes. Experimental tech-
niques to determine physical parameters for the stored
material, to determine strains and stresses in the
stored bulk solid or in the silo structure, and to model
silos and their related phenomena all involve tech-
niques that are very complicated to both develop and
implement. Many of the techniques that have been
developed have lacked certainty and in consequence
many results have been questioned.

3. The CA-Silo Project

There is clearly justification for research into silo
problems. What is equally apparent is the need for a
co-ordinated approach to silo research. This section
outlines how CA-Silo was conceived, and how the
activity planning for the project was undertaken.

3.1 Origins of the Project

It is often difficult to look back and determine the
starting point for such projects, but in this case it
was an informal discussion at a silo meeting (Silos –
Forschung und Praxis, Tagung '88, SFB219) held in
Karlsruhe in 1988. A group from the researchers pre-
sent identified some silo research that was being
duplicated; further, it was evident that some existing
research knowledge had not been well disseminated
or had not been widely enough understood. The
potential inefficiencies were obvious.

Funding sources for silo research are both limited
and scattered, as the solution to problems in the stor-
age or processing of bulk materials tends to be spe-
cific to the different industries involved. The number
of active research groups in Europe is limited and the
technical and research expertise that does exist is
diverse. Many branches of engineering are involved
with the design and manufacture of silos. Agricultural
Engineers, Chemical Engineers, Civil Engineers,
Mechanical Engineers and Structural Engineers have
all applied their knowledge to silo problems. The dis-
semination of understanding is therefore correspond-
ingly diluted. However, in practice, most design
problems are inter-related and effective solutions require
expertise from more than one traditional discipline.

The group therefore concluded that international
collaboration between disciplines would extend funda-
mental understanding of silo problems significantly.

3.2 Concerted Actions

Bringing together research activity from different
member states was an important strategic element of
the EC Research Programme in the early 1990s. A
first project proposal was not successful, but a revised
proposal was put forward by seven partners from five
different member states. They were Danish Building
Research Institute, Denmark; Technische Universität
Braunschweig, Germany; University of Karlsruhe, Ger-
many; University of Edinburgh, UK; T.N.O. Building
& Construction Research, The Netherlands; Labora-
3.3 CA-Silo Objectives and Activities

The primary objective of CA-Silo was to bring “concerted action to the silo research community”. It was the task of the Steering Committee (§12) to outline activities that would enable these objectives to be met.

The first activity was to bring together all those known to have an active interest in silo technology at a plenary meeting. This was held in Delft in 1993. Researchers were asked to make presentations outlining the strategic objectives of their work; industrialists were asked to formulate their main interests, and to identify substantive problems. After the meeting the Steering Committee embarked on a number of activities grouped in a number of broad headings:

- determining the current “state of the art”
- initiating collaborative projects between active laboratories
- supporting exchanges between established groups
- involving industry, and
- identifying research requirements for Codes of Practice, Standards and design guides.

“Working Groups” were established as a mechanism to administer the CA-Silo project. Each working group had an influential researcher as its Chairman. The scope of the working groups was then somewhat pragmatic, based on a mixture of the Chairman’s interests and the subject area as well as the logistics of meetings in limited available time. Each working group was required to produce its own state-of-the-art report. Discussion within the group led to the formulation of sets of working papers, which were then distributed to non-attending members for comment and agreement on remaining technical problems. In some groups the discussions were extensive, in others less so. It was not possible in all cases to remove disagreements, but where these occurred, to recognise them and use them creatively. An outline of the activities is given below (§4).

Having established the state of the art, the groups were invited to move on to active collaboration on agreed objectives, create links and exchanges, and involve industry in the determination of best design practice and the future needs of European codes. These subsequent collaborations were carried out by the research groups then most active, based on proposals approved by the Steering Committee, and are described later in this paper (§5).

4. The State-of-the-Art Report

There were seven working groups, and in effect each has contributed to a part of the resulting book (Ref. 1) – the form in which the reports were eventually published. There are over 40 contributors to the 56 Chapters, resulting in over 800 pages in the final form. In addition to the six parts outlined below in this section (§4), the seventh part describes an industrial survey that was carried out, and a synopsis of the research work needed to support ongoing code work. These were also part of the CA-Silo project, and are described in §6 and §7 below.

4.1 Silo Flow

Of all the areas of work covered by CA-Silo, the one covered by the working group on “Silo Flow” was perhaps the broadest and most difficult to define. “Silo Flow” covered not only the work associated with the determination of conditions for flow to occur in silos, but also the sophisticated testing needed to determine characteristics of the stored bulk solid. There was a potential overlap between the work related to material characteristics for determining flow, and that related to constitutive relations for numerical models. However, the material characteristics (and appropriate methods) have been outlined in both contributions to the state of the art with relevant emphasis.

Silo flow is an area in which industry is actively involved, and the development of continuous monitoring, control and flow promoting devices has been industry led. Wherever there is an industrial lead, there can often be commercial considerations to the research carried out. Nevertheless, this state of the art (Ref. 1, Part 1) has produced extremely useful contributions from a variety of sources.

The state of the art on silo flow is divided into three major parts. The first deals with the testing associated with the stored material and/or the silo material, looking at the problem from both the fundamental and the practical point of view.

In steep-walled mass-flow silos, the flow pattern of the material is well known, and based on the work of Jenike in the 1960s can be confidently predicted. The first-in, first-out characteristic is useful, particularly for biodegradable materials. No stagnant zones form during discharge of bulk solids.

In funnel-flow silos, a flow channel is formed within stagnant material, the funnel-like shape of the flow...
channel being less predictable. A pressure peak can occur at the intersection of the boundary line with the silo wall (and is often thought to be the cause of many silo structural failures). Knowledge of the shape of the flow channel and its dependence on the flow properties is therefore required, as it may have a substantial impact on the economic structural design of silos.

In either case, knowledge of the properties of both bulk solid and silo is necessary to predict flow within the silo.

The second section deals with the flow pattern within a silo. This can be influenced by placing inserts into the silo, by aeration, by vibration or by mechanical activation. Inserts may be needed not only for improvements of the flow pattern but also for introduction of purge or drying gases or for blending purposes. These can have a significant impact on the pressure distribution in the silo. Many codes and standards do not give rules for loads on or from inserts because of the lack of fundamental understanding of their behaviour, and some recent research on this topic is also presented.

Finally, the state of the art provides a critical review of the discharge and flow metering equipment currently available.

The breadth and change occurring in this field are noted by the leaders of this working group, and the suggestion is made that such a project should be run “every 5-10 years” to ensure updates of the information available. Clearly this evinces the need for such collaborative projects, and for some joint industry/government funding on a co-ordinated scale.

4.2 Concrete Structures

Creating two separate sub-sections for concrete and metal structures, each one identifying structural actions and the effect of those actions, caused some concern. However, with silos the division is justified by some of the fundamentally different characteristics of concrete and metal structures.

Concrete silos are relatively stiff structures, often formed by using slipforming, a continuously sliding formwork technique. Other forms of concrete silos include rectangular or polygonal silos, possibly using precast panels. Concrete silos are especially sensitive to tensile stresses. Tensile stresses are introduced mainly by load perpendicular to the structure. However, because of the stiffness of the structure, tensile stresses may also be introduced by thermal action and by differential settlements.

This group consequently focused (Ref. 1, Part 2) on loads particular to the silo form, including bottom loads, and to the structural consequences of temperature changes and differential settlements. Attention is also paid to earthquakes and dust explosions.

Dust explosions can occur spontaneously with disastrous consequences if appropriate conditions arise in the silo and sufficient energy dissipation cannot take place. This is a more significant problem with concrete structures, and so a proposed design method for vent openings has been outlined.

The key topics for research in concrete silo technology are given in a final section. They include soil-structure interaction, earthquake effects, temperature effects in multi-cell silos, and concrete performance in relation to wear.

4.3 Metal Silos

Metal silos are used for storing a wide range of bulk solids and are built in many different forms and sizes. The mechanisms for load carrying and the potential failure modes are generally governed by the thin-walled nature of the structure.

In steel and aluminium silos the critical load patterns are different from those in concrete silos. Many potential failure modes are both sudden and catastrophic and can occur under rather unpredictable conditions.

The two common structural forms have different characteristics. In the curved shells associated with circular planform structures, there is a complex structural response; less well known is the sensitivity to small imperfections that, under some conditions, can be critical. Bursting failures are rare, and metal silo design is mainly governed by other criteria. Rectangular planform steel silos are also used for their simplicity of construction and adaptability, but they are not as intrinsically efficient as shell structures. However, greater economy might be achieved from them with the development of new design philosophies.

The state of the art (Ref. 1, Part 3) addresses in turn the main design problems for metal structures. For efficiently designed metal silos, buckling failure will be a major design criterion. Axial compression occurs not only from frictional traction, but also from unsymmetrical lateral loads from the stored bulk solid. Alone or in combination, these effects can produce high vertical stresses in the wall of the silo. Minor deviations in the wall, the presence of residual stress, local pressure variations within the silo and local variations in stiffness of the stored bulk solid can all affect the buckling load.

Conical shells are used for hoppers and for roofs in circular planform silos, and their design – often a
rather specialist function – is described.

Wind loading can sometimes be the design criterion for empty metal silos; particularly in squat silos, wind pressures can be more significant than those imposed from the stored bulk solid.

The Working Group again identified key areas where future research was needed. These include the effect of real geometric imperfections on silo strength, wall stress patterns caused by unsymmetrical pressures, conditions for buckling under high local stresses, eccentric discharge and how to determine when failure might occur, and criteria for economic designs of rectangular silo structures.

4.4 Numerical Simulation

The inclusion of the state of the art in numerical modelling (Ref. 1, Part 4) is essential, but also to some extent one of the most contentious areas of work. The area is not mature, and developments are still relatively rapid. Many research workers have been active in the development of various numerical modelling approaches. Any concerted action needed to ensure these groups conversed, and it was recognised from the outset that the creation of the state of the art in this activity would be likely to produce a more varied outcome than in some other contributions, and that agreement within the group might be more difficult to obtain. For instance, while some models seek to represent every detail of a silo and to be “accurate”, others may seek to sacrifice some of the accuracy in an attempt to simplify the characteristics of the model.

The different models focus on various aspects of silo technology such as the complex behaviour of the stored granular materials, the different silo geometries and characteristics, the interaction between the stored material and the silo walls, and the different process situations to be addressed (e.g. loading or unloading etc.).

Stored bulk solids exhibit particular mechanical behaviour. This may include non-linearity, stress or strain dependency, plasticity, and dilatancy. Such phenomena need sophisticated modelling. Cell geometry varies not only globally, but also because of local singularities such as eccentric outlets, inserts or internal ties.

The friction coefficient between the silo walls and the stored material is difficult to model, as it may in reality be extremely variable, and depend on the stress levels. Similarly, the load and structural response may be a coupled problem; wall deformations can drastically affect wall pressures.

The different mechanical actions of filling (increasing density, small strains) and emptying (dilation and large strains), and the switch from one to the other can lead to complex phenomena. Asymmetry resulting from apparently symmetric conditions can be difficult to model.

Many of these problems are dealt with in the state of the art, and in particular examples of the use of both the classical continuum approach (the Finite Element Method – FEM) and Discrete Particle Models (DPM) are presented. As in any numerical modelling, the choice of appropriate constitutive equations for the material model is critical, and some alternatives have been examined. In addition, stochastic finite element analysis has been introduced, and contributions looking at the basis for choice of model and method are presented.

Advanced models are able to deal with a range of problems, and an extensive initiative in Germany (the SFB programme) enabled significant progress to be made. Nevertheless, some apparently simple problems cause significant difficulties for the differing numerical models. These include:

• modelling of material behaviour during discharge,
• prediction of flow patterns and conditions of no arching,
• simulation of heterogeneities, segregation, and anisotropy due to the filling process,
• influence of eccentric filling and discharge.

Some of the projects described below (§5) endeavoured to produce further collaboration between active groups.

4.5 Silo Tests

The group working on silo tests was formed to represent those workers (research-based or from industry) who had a direct knowledge of the variety of output that could be obtained from tests on silos. In experimental conditions there is a great deal of variability. There is often an interaction between the behaviour of the stored bulk solid and the structural behaviour. An ideal objective of the group's work was to provide detailed guidance on features of silo tests that should be recorded for the benefit of all future applications of the results.

The state of the art (Ref. 1, Part 5) reviews the conditions of both the stored bulk solid and the silo itself that should be recorded in any silo test. Key elements of the data include the properties of the test silo, the properties of the stored material, the instrumentation of the silo, and the test conditions.

Along with proposals for data to be recorded, a mech-
anism for the presentation and processing of the collected data is presented. This might facilitate transfer of data between sites.

4.6 Experimental Techniques

The effectiveness of silo tests is heavily dependent on the experimental techniques employed. The techniques employed in the measurement of pressures and stresses in silos can differ noticeably from those used in other branches of experimental mechanics. For example, when dealing with relatively stiff elastic bulk solids, it is essential that only very small displacements occur in the cell face of pressure measurement devices. If cell face displacements are too large (in some cases this is of the order of microns), the measured pressure will be a significant under-representation of the pressure at that position. Conversely, if the stored material is very flexible, a stiff cell placed in the bulk solid may interfere with the development of stresses within the stored material.

The contributions to state of the art in Experimental Techniques (Ref. 1, Part 6) are from active researchers who have addressed such demanding problems. Along with criteria for the determination of various pressure readings in silos, alternative strategies are examined. Measurements of such phenomena as cracking, moisture and flow patterns are addressed by specialist techniques. Finally, the criteria for carrying out experiments are examined.

A survey of existing silo test facilities revealed that the number is small and that each facility is built for a specific function. The need for research collaboration could not be more emphasised than in this field.

The working group identified key problems as:

- the interchangeability and calibration of pressure measurement devices
- measurement of local density in situ
- measurement of interstitial and atmospheric air pressure
- measurement of moisture in stored bulk solids
- flow visualisation techniques
- the use of wall strain measurements
- model laws and scale errors

5. Collaborative Projects

A key objective of CA-Silo was to bring together groups or individuals that were already working on specific problems. The aim was to add value to existing projects. CA-Silo funded these collaborative activities after approval by the Steering Committee. They are described very briefly below. Fuller details and publications are available from the co-ordinators of each activity (indicated by the bracketed number [ ] in the sub-headings and listed in §12).

5.1 Imperfections in Metal Silos: Measurement, Characterisation and Strength Analysis [1]

There are several groups working on imperfection measurement and characterisation in Europe, but the application of the studies can vary considerably—from rocket science (conical shells) to more earth-bound silo structural problems. One of the strategic objectives of this project was to bring together a body of knowledge on the subject, and to identify criteria common to all applications that might be especially relevant to the design of silos.

The three technical objectives in this project were:

- to measure, characterise, and analyse imperfections in real metal silos;
- to perform buckling strength predictions for metal silos, identifying imperfection modes and amplitudes; and
- to examine the relationship between measurements and imperfection characterisation.

A Workshop held at INSA Lyon (France) provided the final focus for this project. Sixteen papers were presented, each forming an important output from the work of the contributor, and following discussion, agreement was reached on a number of issues relating to imperfection modelling.

Two of the key outcomes from this project relate to construction quality and modelling tools. It was agreed that construction quality was likely to be a significant feature in the design of silos, and in particular the presence of residual stress would be significant to the buckling strength of the shell. In terms of modelling techniques, in many cases axisymmetric imperfections remain a useful tool in modelling real imperfections.

5.2 Comparative Evaluation of Numerical Methods for Predicting Silo Phenomena [1]

There already existed a UK-based project to determine the state of the art in numerical modelling in silos. CA-Silo could add value to that project. The idea of the CA-Silo project was to bring researchers in this field together and ask them to attempt to solve an idealised identical problem using their own procedures. While anonymity would be retained, each researcher would be able to identify their own position in the "pack".

Both Discrete Element and Discrete Particle Models (DEM), and Finite Element Models (FEM) were used in the project. There were only a few full 3-D FEM models. DEM models could only handle relatively
small numbers of particles. Thus, plane strain 2-D analyses were a natural choice. The collaborating researchers were set two problems. The first was a filling problem, while the second involved discharge from a silo.

The project concluded that, in general, there is a very wide scatter in predictions from different programs even when given carefully defined identical initial data. The finite element method generally cannot represent the filling process at all, but must take this as an a priori assumption, while the discrete element method has difficulty in capturing such elementary properties as the angle of repose, or the stresses in the stored solid.

5.3 Finite Element Modelling of Real Silos: Comparison with Full-Scale Tests [2]

Some of the problems in silo research remain unaddressed. One of the challenges for the future will be the calibration of numerical models against reliable data from full-scale silo tests. This collaborative project was the tip of that iceberg. It took data from tests at Chartres (France), at Karpluslund (Sweden) and at Watford (UK), and aimed to compare finite element predictions (essentially wall pressure) with experimental measurements from these instrumented real or large-scale model silos. Different modelling strategies were investigated.

The conclusion was that a satisfactory model does not readily exist: a dynamic calculation gives a suitable solution based on a sophisticated model, but it does not reach the permanent flow stage. Quasi-static approaches are more efficient for this, but they are not able to represent the evolution of the stress distribution just at the beginning of the discharging process. Neither of the two approaches reached acceptable comparisons to experimental data.

5.4 Improvement of Stress Measurement in Silos [3]

The problem of pressure measurement in silos is widely recognised as an extremely difficult and specialist task. A collaborative project was established to determine the extent to which the challenge of pressure measurement in silos was being met, and the initial survey of all potential CA-Silo participants revealed the known difficulties in constructing pressure cells and hence rarity of appropriate pressure cells. It was therefore entirely appropriate for this project to focus on technology transfer, and to ensure that the existing knowledge would be maintained among those interested.

The group identified a need for validation criteria when designing pressure cells (calibration of pressure cells with different stiffnesses), and used the project to form a comparison of the calibration procedures adopted in a special chamber and in a geotechnical centrifuge. A short-term exchange had shown that transfer of the techniques involved in the use of embedded normal stress cells was possible. The subsequent focus on factors enhancing the technology transfer (e.g. the effect of personal factors when mounting the cells and the need for standardisation of the placement procedure) was a natural progression.

The work has shown that suitable technology exists for the determination of in-situ stress, that calibration is possible, that with appropriate training the technology can be transferred, and that placement of the device is critical and can be made less variable by means of placement devices.

5.5 Patch Loads and their Use in Metal Silo Design [1]

This collaborative activity was based on existing work being carried out at the three laboratories involved. It was designed to focus this work, and bring it more rapidly to the state of being useful in codified rules. The work at the University of Edinburgh (UK) aimed to determine the effect of patch loads on circular metal silo structures, taking into account different forms and positions for the patch of pressure, while work at the Technical University of Graz (Austria) aimed to determine the effect of a patch load on silos that are stiffened, by comparing stiffened and unstiffened designs. Brunel University (UK) looked at the effect of a patch load on rectangular planform metal silos.

The study concluded that the patch load problem in metal silos is very complicated, and requires much more study if patch loads are to be used generally in silo design. With patch loads, there appear to be no simple ideas that can easily be used to generalise the effects of real pressures on silos of different geometry and thickness, which store different solids and which could be supported in different ways.

In general, the patch load is not needed in many rectangular silos, and the standards should be modified to identify the geometry where patch loads are really needed to ensure structural integrity.

In circular planform silos, use of a patch load concept aims at ensuring a robust design approach to deal with asymmetric actions in apparently symmetric systems. Yet the location, distribution of patch pressure and the effect of the patch adopted on the mod-
elled design may be inappropriate or disproportionate; care must be taken to model a realistic silo.

The results of this project are important in relation to the drafting of codes or guidelines for the design of silos. However, from this study it is clear that the relationship between measured silo non-symmetric pressures and suitable models for patch load definitions needs much more work.

5.6 Stochastic Behaviour of Loads from Bulk Solids [4]

In-line with the approach to structural loads adopted in the Eurocodes (CEN standards), it is clear that in the longer term, silo loads should be prescribed in probabilistic terms. To investigate these possibilities, a smaller (almost feasibility) study considered a set of wall pressure measurements taken from a full-scale concrete silo that had been used for storing soya meal.

It can be concluded that it will remain a challenge for some time to define load models for practical use based on the stochastic approach. Accurate and adequate collection of data from pressure and strain gauge measurements in a large range of silos with different stored solids are needed.

5.7 Load Parameters [5]

Parameters for representing the physical behaviour of stored bulk solids are included in all models of silo loads that are used in codes of practice, design recommendations and standards. However, such parameters are often not well defined and are dependent on the test methods used and the individual interpretations of results. As they are listed in official documents, safety considerations have influenced the published values of parameters. The new CEN, ENV 1991, part 4, Actions on Silos and Tanks, refers to load parameters determined directly from materials testing, but there is little experience with the accuracy of this approach.

This CA-silo project aimed at asking each of the contributors to provide data from their own work which, when combined with others, would form a major contribution to the European database on load parameters. It aimed:
- to compare the load parameters given in the proposed European standard with those obtained from material tests on some of the listed materials;
- to compare results obtained from different laboratories and methods;
- to evaluate safety levels obtained from using code values, as opposed to those obtained using load parameters from test results.

The material testing was carried out in different apparatus. These include triaxial tests, circular and square shear-boxes and apparatus for direct measurement of the pressure ratio, K. Some tests in the circular shear-box were carried out using the Jenike procedures and were intended for flow determination. For these tests the consolidation procedure deviates significantly from the soil mechanics tradition.

The project concludes that the load parameters listed in the ENV and those derived from the material tests conform reasonably well in many cases. There are, however, also cases where the agreement is not satisfactory, especially due to larger variability of the measured values than the so-called conversion factors can be assumed to take into account. This is certainly true for coal, and perhaps also for flour. Too few parameters have been obtained from triaxial tests and direct K-measurements to judge if these – presumably more accurate – tests give systematically different results. The measurement of reliable and relevant wall friction coefficients is a severe problem. If the wall friction depends on whether the normal load is increasing or decreasing, it is the value for increasing load that should be the relevant load parameter. However, for coal and wheat, it is seen that the wall friction measured directly in a silo may be significantly larger than the value obtained from shear tests.

From the results, it became clear that to date, there is a significant influence of both the testing method and the interpretation of the material tests in obtaining load parameters for the structural design of silos. This means that further actions are needed.

5.8 Concluding Comments on Collaborative Projects

The collaborative projects were particularly successful where individuals or groups were already active in the field. CASilo was not able to fund any substantive work, although some of the work necessary for the collaboration was funded. This essentially meant that participation was limited to those with current research grants, or time/funding available to work on the problems; consequently, the number of potential participants was limited. Further comment is made on this issue below (§10).

6. Short-Term Exchanges [6]

The CA-Silo Programme supported a number of short-term exchanges. A pre-condition was that the parties involved were essentially active researchers. Some of the short-term exchanges led to fuller collab-
orations in other elements of CA-Silo (e.g. one visit from Italy to UK led to a contribution to the work on imperfections in metal silos — see §4.1). In other cases, young researchers from one group have gained substantially from experiencing first-hand the work being carried out by another group. There are few enough active silo groups for this to have been an extensive activity.

Another short-term exchange funded a joint visit by an academic from Germany and an industrialist from UK to report on a Dutch silo with problems. By bringing their joint expertise to bear, this problem can now be fully reported with appropriate technical detail.

7. Industrial Involvement

Silo research needs industrial guidance; the majority of silo problems impact on industrial efficiency. Industry was encouraged to participate actively in the project from the outset. At the Delft meeting (see §3.3), industrialists were invited to make presentations and to participate in the discussions which formed the basis of the work programme. After Delft, some industry contributors were asked to sit on the Steering Committee and to sit on the working groups discussing the state of the art. Twenty-two of the contributions to the chapters are from industrial participants.

To obtain an industrial point of view on research requirements, a wide-ranging group of companies was asked to complete a questionnaire. This is also included in Ref. 1 and has been useful in helping shape conclusions on future research.

It is evident that the project generated interaction with elements of industry. However, it is also evident that no particular industry is prepared to take responsibility for major investments in the basic knowledge that still needs to be generated.

8. Research Requirements

As part of the work of each group, it was agreed that a common element of output should be the identification of research needs within that sphere of work. In each case, the work is identified in the appropriate summary of each part of Ref. 1. Research requirements are also evident from some of the conclusions from the collaborative projects. In consequence, the project has raised a number of questions for future workers, and a number of specific requirements for pre-normative research have been identified.

A survey carried out by CA-Silo identified those areas where significant improvements and further work are necessary for the effective implementation and acceptance by the silo community of CEN guidelines. Ten projects have been identified, and of these, the three with highest priority were:

- Calibration of parameters for stored materials
- Loads in silos with extreme eccentric outlets and/or inlets
- Silos with internal ties

An initial study of the calibration of material parameters has been carried out (see §5.7) but there is further work required. The other two areas require such significant efforts that these need separate funding. Other major areas requiring research are:

- Loads in squat silos
- Seismic actions in silos
- Calibration of Patch Loads with measured properties (again, some initial work has been carried out in a collaborative project)
- Dust explosions in silos
- Loads in silage silos
- Actions due to differential temperatures
- Buckling strength of metal silos under eccentric loads

Efforts to obtain funding for this work have, so far, been unsuccessful.

9. Project Outcomes

The completion of the state-of-the-art report in book form was a major achievement. The book (Ref. 1) contains contributions from not only major European silo researchers, but also a considerable number of industrialists. It is confidently expected that it will be used as a primer for many future researchers and designers.

The collaborative projects were limited, but the quality of work carried out was high. The added value to the projects from multi-national and multi-disciplinary participation would not have been possible without CA-Silo.

CA-Silo identified future research needs. Not only did the active researchers in CA-Silo identify research needs, but a survey of industrialists also provided insights into their perceived research requirements. Not surprisingly, there was much agreement between the two sets of responses.

10. Project Management Issues

A definable “silo industry” does not exist. There is a collection of industrialists with problems and queries from many sectors; the common interest is the need
for safe, reliable storage of bulk solids. The level of expertise varies tremendously from sector to sector; some industrial sectors lead research while for others research is the last tool to be used.

The Delft Workshop held by CA-Silo brought together a range of different interests, and provided a focus for potential contributions. All attendees were funded, and all (consultants, contractors, industrial users and researchers) provided a brief (2 or 3-minute) synopsis of their research, their industrial interest, or their current problem. This formed the diffuse basis from which CA-Silo was generated.

CA-Silo activity needed an operational focus, and this was initially the state-of-the-art report. Working groups had been established, and all those who attended the Delft meeting were kept involved at different levels.

A wider, more iterative and controlled process was part of the initial concept for the generation of the state of the art; this review process would have led to in-depth discussion of key issues, greater agreement on areas of conflict, and a more homogeneous coverage of the different items. However, this was not approved by EC as part of the project plan, and so the state of the art was brought to a premature conclusion in 1996. Despite this restriction, the contributors were motivated to maintain their engagement and complete the work.

Later in the project period, direct collaborations became a key activity. The collaborative projects were conceived as a method of bringing together active researchers and adding value to their joint work. This was achieved along the lines of the original CA-Silo proposals.

The difficulty here, however, was that research awards (whether academic grants or industry-based contract research) are quite carefully monitored with project management often an important aspect of any approved contract, and with time-scales, schedules and deliverables as key items. Lead times are often years rather than weeks. It is therefore difficult to take advantage of the potential added value unless chosen objectives are almost identical; but if objectives are that close, unwanted duplication is a potential problem.

CA-Silo resolved the duplication issue by bringing together different institutions working on related problems and by asking them to solve a common problem using their individual approach. Examples include the project where several institutions used different numerical models to solve the same problems, and the project where different institutions measured properties of stored bulk solids.

One feature that could not be resolved by a concerted action is the fundamentally disparate nature of the sectors with interests in silo research. Research funding is difficult to obtain without industrial support, and while a follow-on project in, say, powder testing may obtain support from process industries, it is unlikely that the different firms involved in the structural design process could be so united. To fund the fundamental research work needed to produce a pan-European design guide or Code of Practice, an even wider perspective is required.

Many failures could be avoided with improved understanding. Having reached consensus on the research need, it is frustrating that to date, no mechanism for carrying out the work is available.

11. Concluding Comments

It is now just over two years since the conclusion of the project, and it is an appropriate time to review the outcomes from such a significant project and to suggest ways forward from CA-Silo.

The CA-Silo project confirmed that many of the fundamental phenomena are very complicated and still poorly understood. These problems are too broad-ranging for any single nation state, and international collaboration is clearly needed if the essential potential gains and savings to industry are to be realised in the foreseeable future. This justification for concerted action remains after the project.

The CA-Silo project has shown that a collaborative action can be established to resolve the technically complex problems within this field. CA-Silo has built up a network of groups willing and able to collaborate. This network has involved major research groups as well as consultants and industrialists engaged in silo problems. Future international co-operation in this field has an improved starting point.

CA-Silo was a significant step along the road to greater harmonisation of research priorities, and to better understanding of some of the significant and challenging fundamental technical problems facing designers, producers and users of silos.

12. Acknowledgements and Contacts for further Information

The authors of this paper are particularly grateful to the members of the Steering Committee. Their timely and accurate reporting of elements of CA-Silo for which they were responsible has been a major source
of information for this review. The members of the Steering Committee were:
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The project was supported by the European Community under the BRITE EuRam Programme, Contract BRE2-0128, Project BE 5021.

The four EC Project Officers throughout the duration of this project gave helpful advice, and in particular the authors would like to acknowledge the support of Dr L. Braganza and Dr S. Becker.

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