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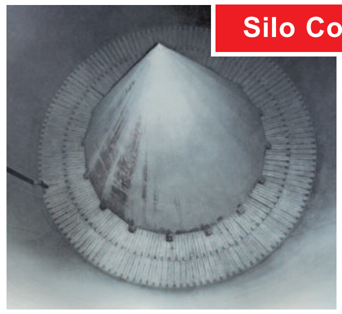

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H05/17/Central Cone Silos from the structural point of view

IBAU HAMBURG

IBAU HAMBURG
Central Cone Silos

from the structural point of view

A HAVER & BOECKER Company

The original IBAU HAMBURG Central cone silo from the structural point of view

THE ORIGINAL: Thousands of this silo type are in operation for many years

General information

The civil design of large capacity silos requires extensive know-how and expertise.

This is mainly fulfilled by the involvement of qualified civil design companies, which are familiar with the state-of-the-art.

Nevertheless, our experience is, that in some cases, local codes, regulations and guidelines are used, that do not take into account the complexity of large silos, as this is e.g. stated in the Eurocode EN 1991-4, or the relevant national codes such as the DIN EN 1991-4 (2005) and DIN 1055-6.

IBAU HAMBURG works for more than 30 years together with the civil design company Peter und Lochner with regard to the design of the central cone silo.

This brochure describes the construction principles according to the above norms that should be taken into account by the design company as well as the plant owner.

This brochure focuses on the critical reinforced concrete silo structural elements, such as the central cone, the silo wall in the section adjacent to and below the cone, the silo walls above the cone and the intermediate walls for multicompartment silos.

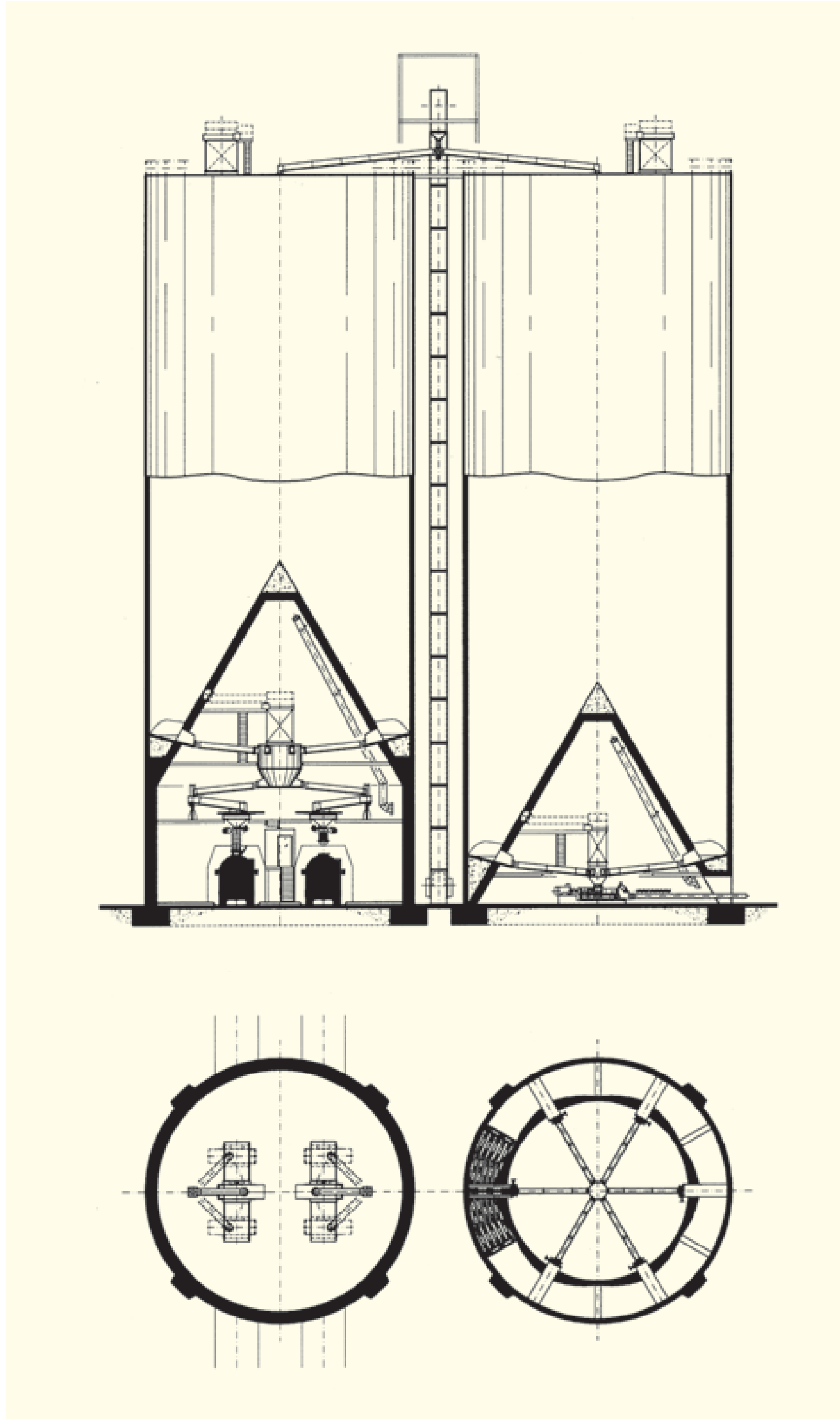
The IBAU HAMBURG Central cone silo – THE ORIGINAL

The storage silo

IBAU HAMBURG introduced the central cone silo to the market in 1975, when the company was established in Hamburg, Germany. The design is mainly used for large storage silos in the cement industry and other mineral industries for cement, raw meal, fly ash, ground granulated blast furnace slag, alumina and similar products. Storage silos for these products have diameters of 10 m to 30 m and even more with storage capacities up to 40000 t and they require an efficient and troublefree emptying.

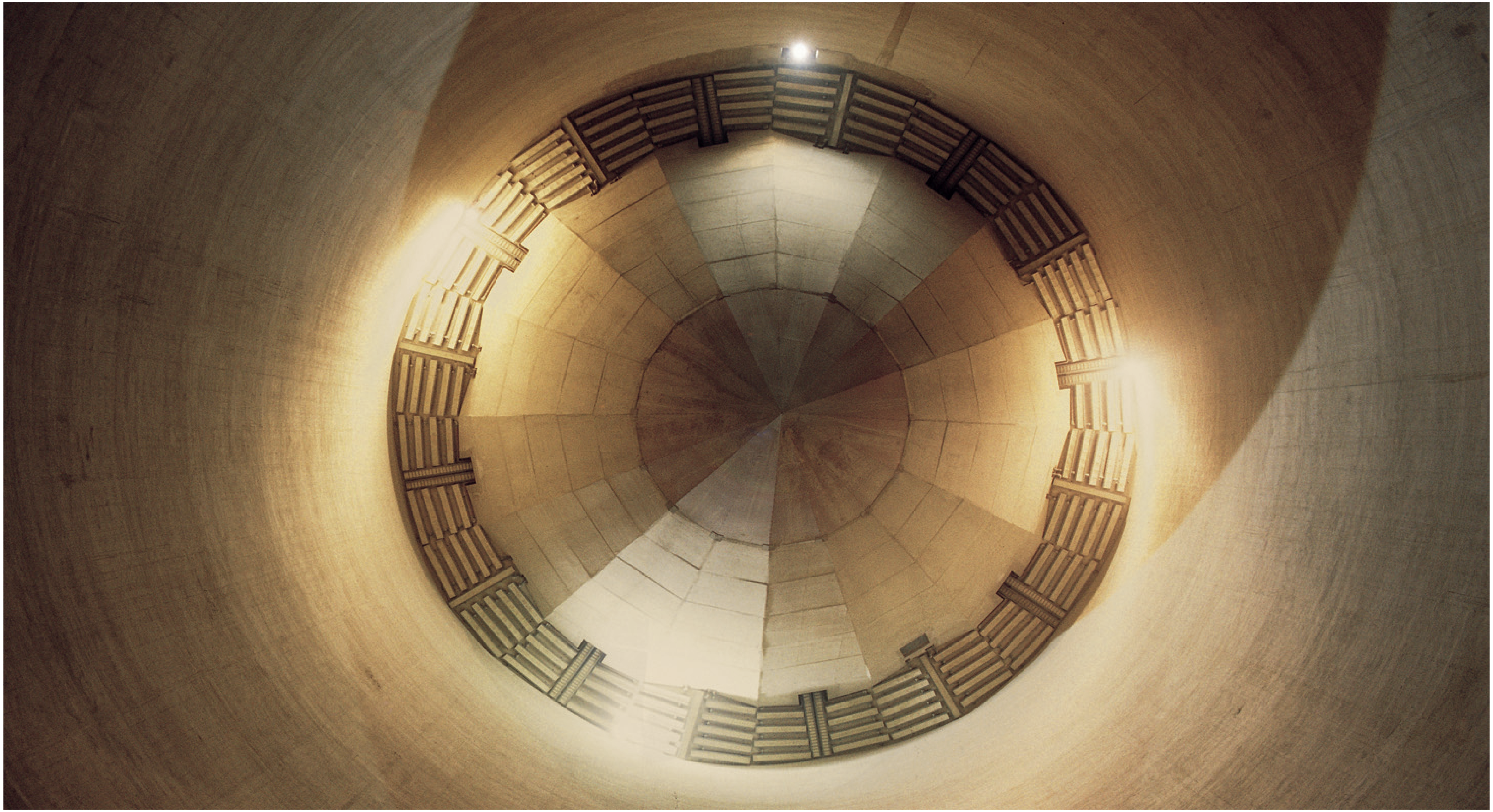
The IBAU Central cone silo has been proved to be extraordinarily successful. Today, more than 7000 units are in operation by various customers around the world, so that the central cone silo design has also been copied by other suppliers. In the original IBAU design for large silos, the central cone forms a ring space on the silo bottom. This is divided into individual aeration sections that are slightly turned towards the discharge openings in the cone with a small inclination.

The silo bottom is equipped with so-called fluidslides that have an air-permeable fabric on the upper side. The aeration air is supplied by a



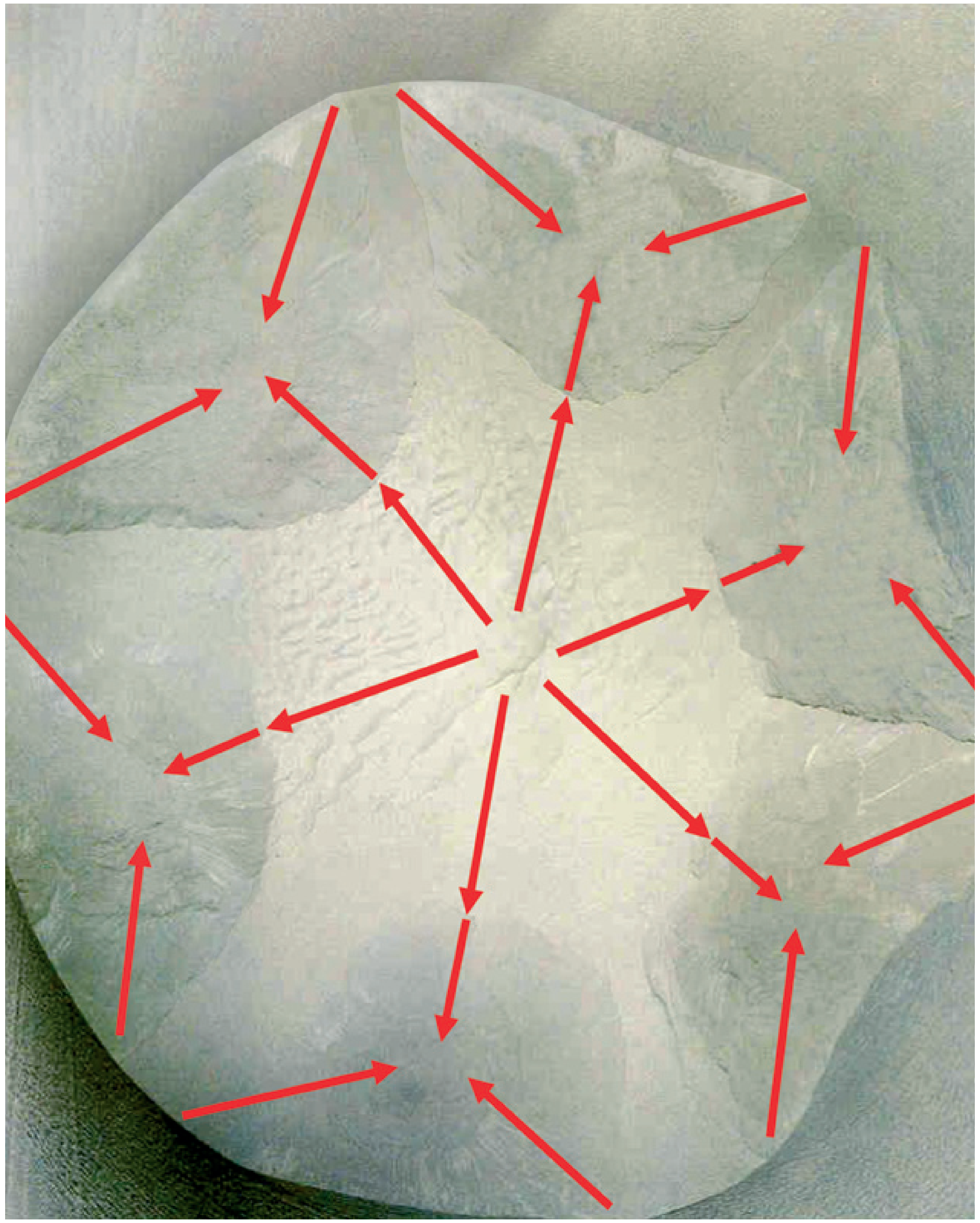
The IBAU Central cone storage silo

The original IBAU HAMBURG Central cone silo from the structural point of view



View into the central cone silo with ring shaped bottom and fluidslide system

The original IBAU HAMBURG Central cone silo from the structural point of view



Flow channels in an IBAU Central cone silo

blower and is led underneath the fabric in order to fluidise the bulk material above. Each aeration section has its own flow control gate and air valve. For the material discharge, the ring space in the silo is aerated section by section so that in a complete cycle all sections have been aerated and the entire material in the silo has been set into motion.

The discharge concept requires only small quantities of air and only a small power consumption of less than 0.1 kWh/t for discharge. More than 99% material recovery is reported by the users and the first in-first out principle still applies for a well designed silo. On the other hand, as only the material above the aerated silo section will get in motion, with the sectional aeration concept flow channels are formed so that the silo discharge is eccentric. In the IBAU concept, the eccentric flow within the silo is controlled by the automated flow control gates, which will discharge only the required flow rate from the silo.

This controlled flow of material corresponds exactly to the consumption of the plant and does not generate, as with other silo systems, an uncontrolled material flow inside the silo, which may damage the silo body. This leads to our motto: „SAFETY FIRST“ by using IBAU silos. Nevertheless, there are also other silo designs with central cones and aeration sections available, where the material flows from the aeration section through large openings directly into the area under the cone without any flow control gates in-between. Appropriate flow control gates are only installed for the discharge from underneath the cone.

IBAU Silos - SAFETY FIRST

IBAU Central cone silos are designed in such a way that the complete material within the silo is in motion during a full aeration cycle of the silo, achieving a high emptying rate of about 99 %.

Secondly, the aeration is designed in such a way, that the flow channels that are formed during discharge are not or only slightly contacting the silo walls. In the picture on page 6 an interpretation of the formation of flow channels in large capacity silos for the cement industry has been given. The controlled flow via flow control gates is the basic concept of the IBAU „SAFETY FIRST“ principle.

IBAU HAMBURG has also been asked to design silos with a depressure chamber. IBAU is aware, that comparing this design with the original IBAU Cone silo assuming an identical number of aeration sections and aeration time, the large openings of the cone dramatically increase the

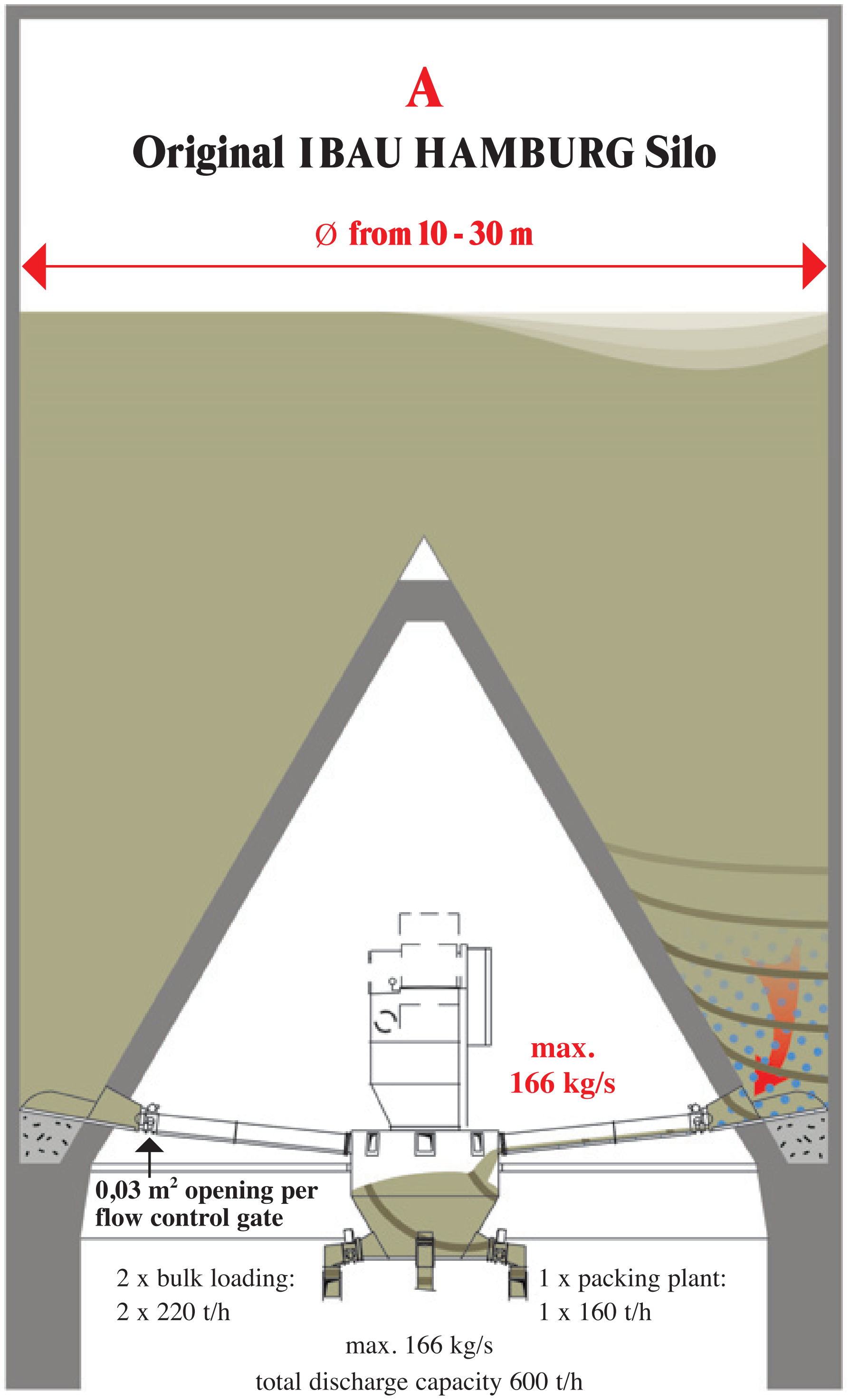
The emptying rate of the silo is more than 99 %

Aeration section and silo outlet

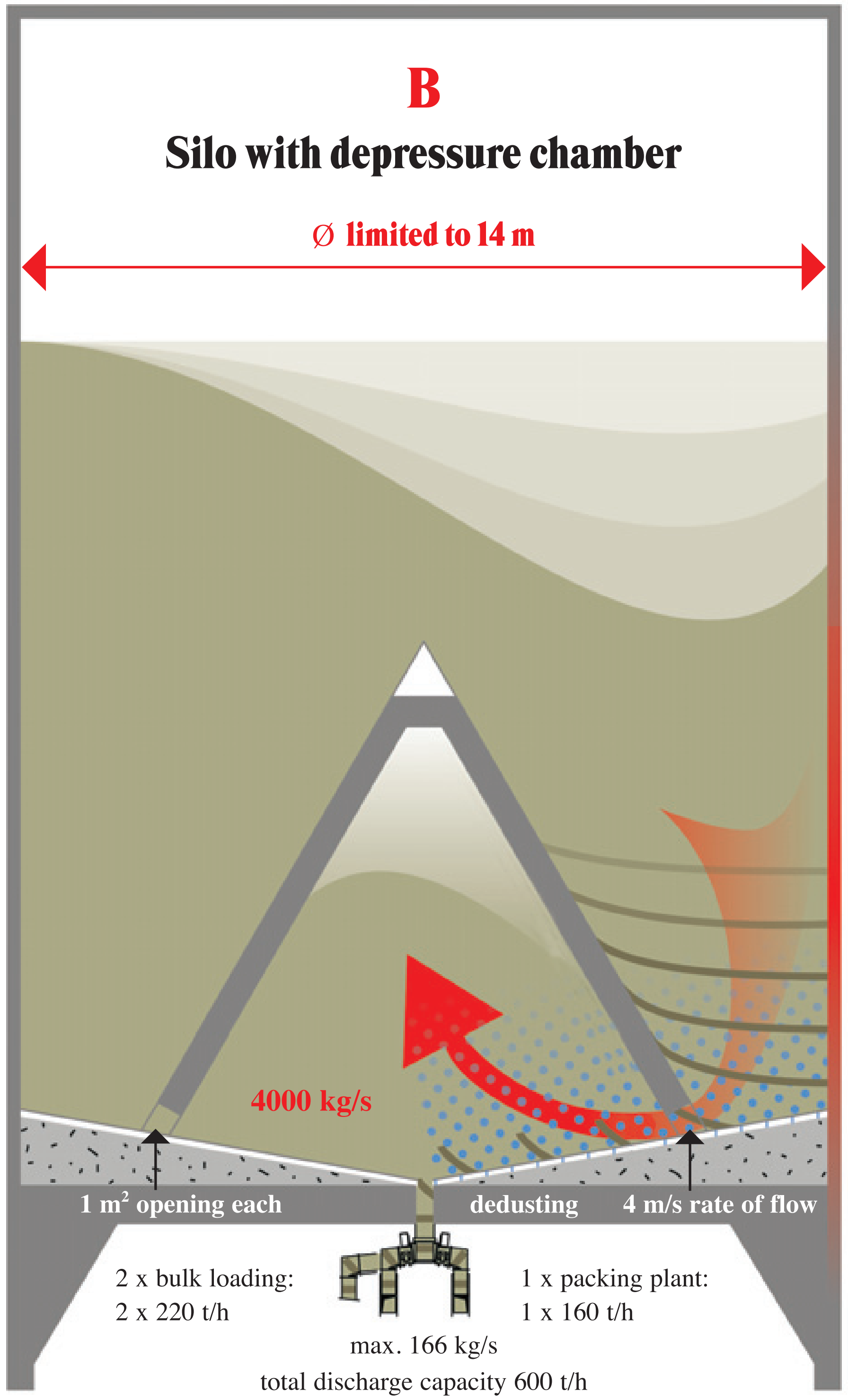
The original IBAU HAMBURG Central cone silo from the structural point of view

A

The original IBAU HAMBURG Central cone silo is used for diameters between 10 m and 30 m.



Calculation example for a silo diameter of 26 m



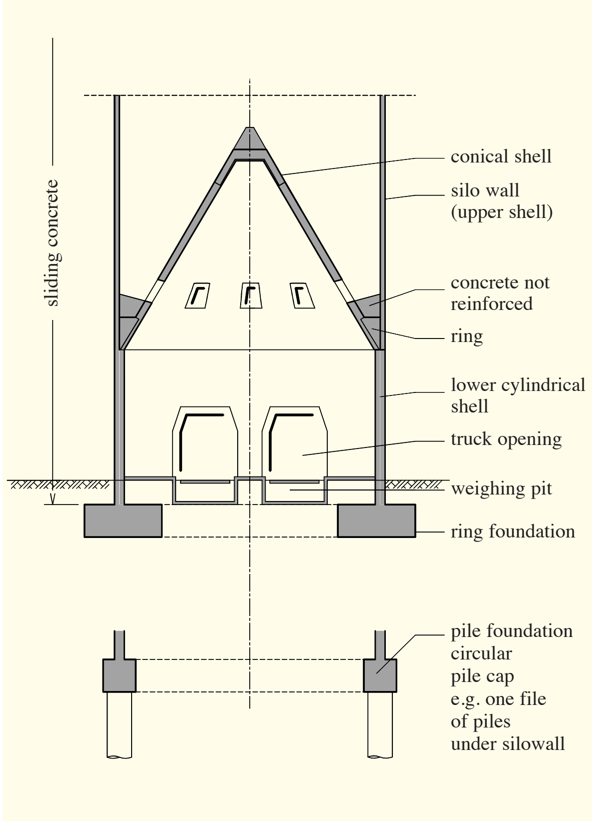
Calculation example for a silo diameter of 26 m

B

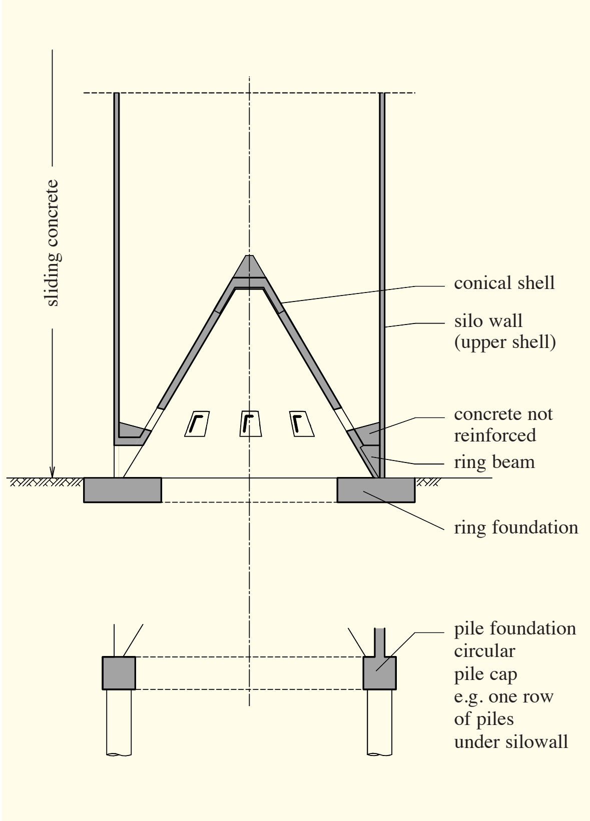
The diameter of 26 m is only indicated for the comparison between the original IBAU HAMBURG Central cone silo and the silo with depressure chamber.

IBAU HAMBURG only uses the silos with depressure chambers for silo diameters up to 14 m.

The original IBAU HAMBURG Central cone silo from the structural point of view



Raised bottom version



Standard bottom version

specific internal mass flows. This internal mass flow increases with the cone size, resp. the silo diameter. These are the main reasons, why IBAU HAMBURG has limited this design to silo diameters of up to 14 m.

The central cone silo from the structural point of view

CENTRAL CONE

The characteristic feature of the silo structure is the central cone, which forms the bottom of the silo compartment. The central cone (inverted cone) is spanning over the complete silo section and is supported only by a setback of the outer silo wall (lower cylindrical shell as shown above). No intermediate supports are required for this structure. The weight of the steel floors for the discharge equipment and auxiliary equipment such as intermediate bin and filters placed below the cone is small compared to the weight of the bulk material supported by the central cone. Therefore it is very economic to suspend these floors from the central cone, which means no additional columns and foundations are required, and the use of steel can be kept to a minimum. A further advantage for the free spanning central cone without additional supporting columns is the clearly defined load transfer to the silo substructure and subsoil.

All loads from the silo structure are transferred to the outer ring wall below the cone. Settlements are equally distributed all over the wall perimeter, due to the symmetry and stiffness of the structure, and restraint forces due to different settlements are normally negligible. The vertical loads from the bulk material and the suspended floors are transferred to the supporting wall by normal compression forces in the direction of the meridian. The horizontal pressures from the bulk material are acting towards the silo centre, which also results in normal compression. Therefore reinforced concrete is the most advantageous construction material for these silos and the amount of reinforcement can be kept low. Due to the shell structure of the cone, bending moments at the bottom of the cone at the transition to the ring beam and at the

SPENNER ZEMENT Multi-compartment silo, Germany

The original IBAU HAMBURG Central cone silo from the structural point of view

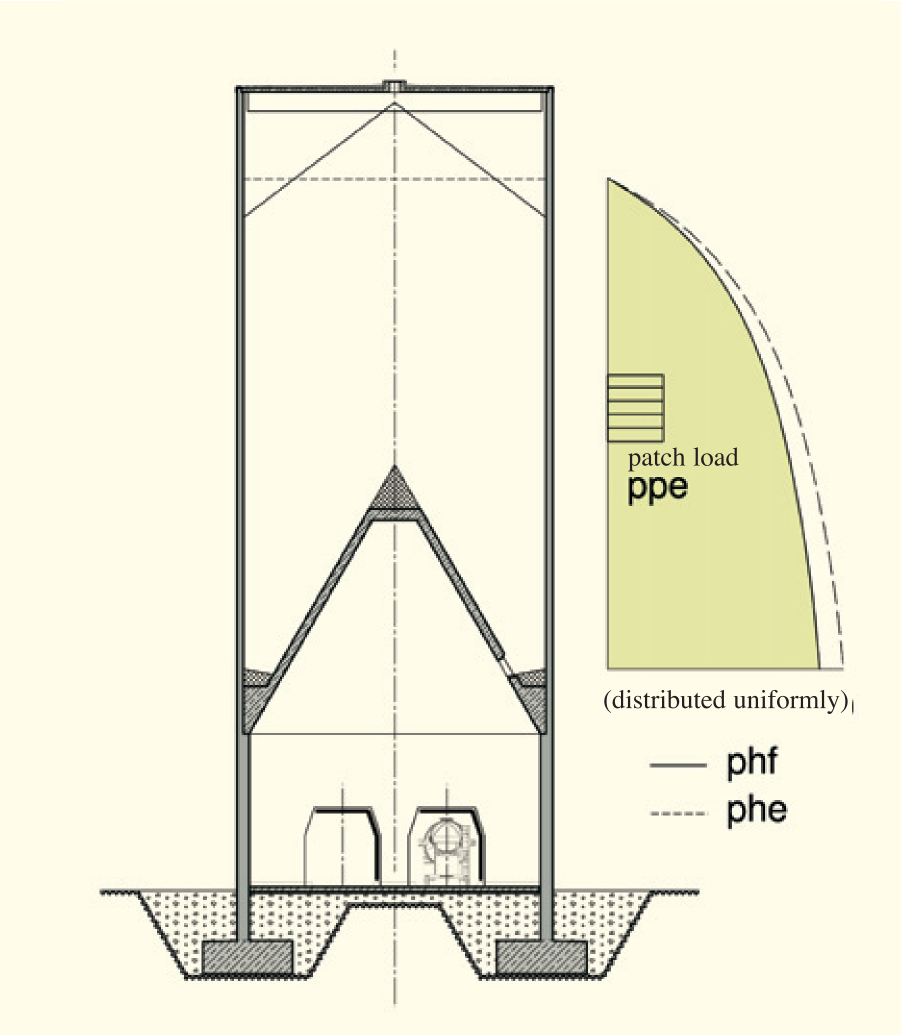
upper edge fade out quickly in some distance from the edges, which means additional reinforcement due to the restraint effect, is required only locally.

RING BEAM

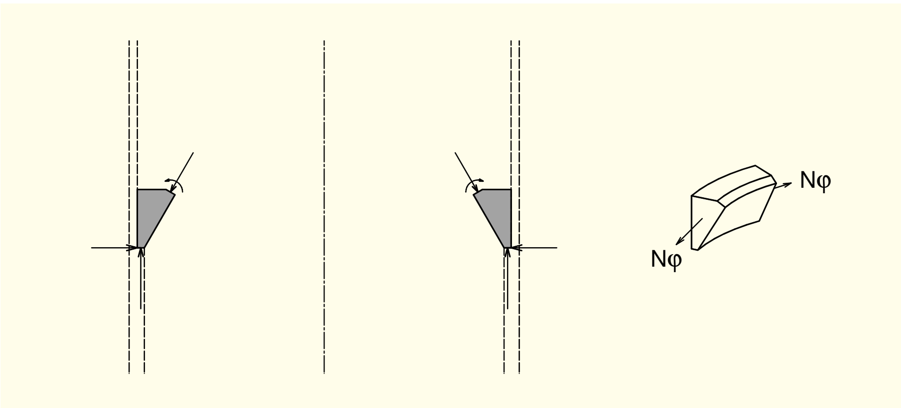
The ring beam located at the bottom of the conical shell transfers the meridian compression forces to the supporting wall, where they are mainly acting in the vertical direction. The redirection of meridian loads also causes horizontal loads, which result into horizontal tension forces in the ring beam. For large silo structures these tension forces can be quite high, so that concentrated hoop reinforcement is required. But due to the size of the ring beam the placement of this hoop reinforcement is quite simple.

From the structural point of view it is sufficient to place the inverted cone on the silo wall without any connecting reinforcement, which means a hinge in the static system between cone and silo wall. The horizontal displacement due to loads and temperature is equal for all members adjacent to the connection.

Due to the orientation of the horizontal loads the displacement is orientated outwards, which results in circumferential tensile stresses. Because of an equal displacement and equal circumferential stresses, tension forces will occur in the ring



Filling pressures in a central cone silo



Stresses in the ring beam

beam as well as in the silo wall adjacent to the connection. The relation of tension forces is corresponding to the relation of concrete sections.

SILO WALL ABOVE THE CONE

The main loads on the silo wall are the loads from the bulk material, which will be applied as horizontal pressures (orientated outwards) and wall friction loads (orientated downwards). There are several codes all over the world, which specify loads from the bulk material.

All common silo codes including the new Eurocode EN 1991-4 predict the same fill pressures from concentric filling and use the Jansen formula, in which the horizontal pressures increase with the height from the silo top to the bottom, based on an e-function and with the silo diameter, the wall friction coefficient, the material specific weight and the horizontal pressure ratio as the main parameters.

Much more difficult to calculate and to predict are the silo discharge pressures, especially when flow channels are formed above the aerated section in the central cone silo during discharge. Practical calculation methods are given in the Eurocode EN 1991-4 as well as the latest revision of the DIN 1055-6, which is mandatory in Germany for the calcula-

The IBAU Central cone silo 25.000 m³ at the Mehrum Power Plant

The original IBAU HAMBURG Central cone silo from the structural point of view

tion of silo loads and which was released in 2005 in Germany together with the Eurocode.

Generally, the stress level of the material within the flow channel is much below the bulk material at rest. Accordingly, there is a pressure reduction in the area, where the flow channel touches the wall and on the other hand there is a pressure increase beside this area over a corresponding length of the perimeter.

The pressure on the remaining wall perimeter is specified as the load due to filling. An illustration of wall loads during discharge is given in the figure on the opposite page. The parameter r_c describes the radius of a flow channel, e_c the eccentricity of the flow channel from the silo centre and l_c the length of the flow channel at the silo wall. According to EN 1991-4 and the German code DIN 1055-6, for silos with large eccentricity ($e_c = 0.5\ r_c$) and assessment class 3 (silo capacity larger than 1000 t) calculations should be performed for no less than three values of the radius of the flow channel, when the geometry of the flow channel cannot be directly deduced from the discharge arrangements and silo geometry. All three sub-load cases have to be analysed for design and the maximum horizontal reinforcement required for these three cases has to be provided.

For the analysis of a cylindrical silo wall for a load case with variable pressures the finite element method has to be adopted, which takes into account the 3-dimensional performance of the wall structure. This means it is not longer possible to perform the structural analysis of the silo wall of a central cone silo with simple equations as it was possible according to the 1987 edition of the DIN code.

Nevertheless, DIN 1055-6, edition 2005 still uses the patch load concept, which shall be applied on the silo wall, at several heights of the wall, resulting in a variable increment over the height. The analysis and design due to a patch load applied on a cylindrical wall has been focused on the bending moments and normal forces, which are caused by the patch load. Shear forces have to be considered in a separate calculation.

The German DIN code DIN 1045-1 for the design of reinforced and post-tensioned concrete specifies the ultimate shear force, which can be taken by a concrete section without shear reinforcement depending on the concrete strength, ratio of reinforcement and stress due to a normal force.

Compression on the section means an increase of the ultimate shear force whereas tension means a reduction.

The shear design of large central cone silos for shear and tension forces caused by the loads due to a flow channel leads to the conclusion, that for usual concrete strength and a wall thickness of 30 – 35 cm there is a limit for these shear forces for a silo diameter of approx. 14-16 m. This means due to this design equation a wall of such a silo without shear reinforcement would not be permissible for diameters > 14 – 16 m when assuming large discharge eccentricity. One solution would be the installation of shear reinforcement, which is not a preferable way for such a large wall area. Another more advantageous solution is post-tensioning of the wall. As described above, compression, which can be gained by post-tensioning, increases the shear capacity of a concrete section.

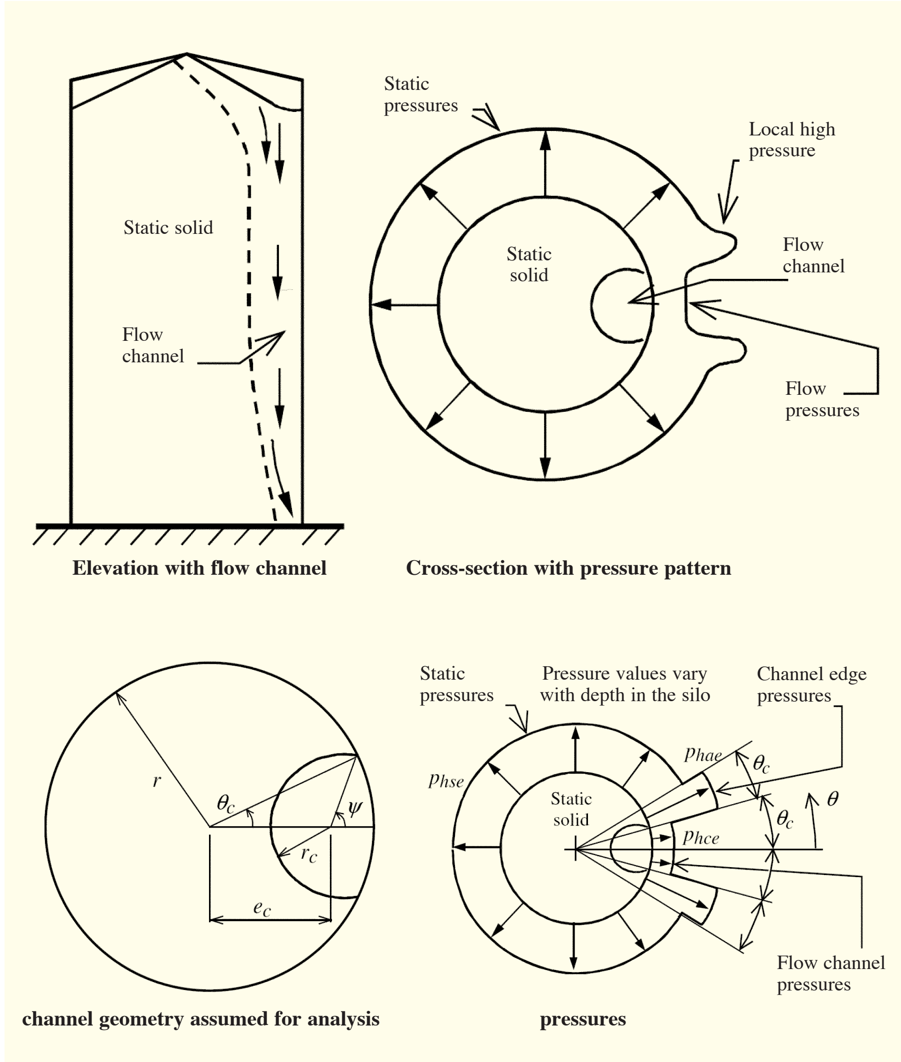
Simultaneously the horizontal wall reinforcement can be reduced by a remarkable amount, because the post-tensioning tendons or strands have a much higher tensile strength than deformed rebars, which means a double positive effect.

The remaining question is the proper ratio of post-tensioning. Because a ring shaped tendon or strand in a cylindrical wall will cause compression only, it is not economic to counteract the bending moments due to loading or temperature drop in the wall by post-tensioning, because this would need very high post-tensioning forces.

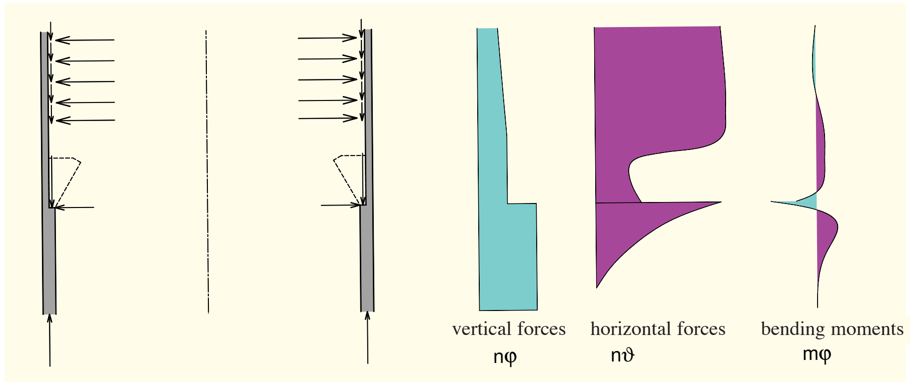
The most economic way is an amount of post-tensioning forces which compensates the tension forces from the bulk material and an amount of inner and outer deformed rebars, which can counteract the bending moments due to loads. With this combination the control of crack width due to temperature restraint stresses in the wall is very economic and the amount of post-tensioning steel and deformed rebars is well-balanced.

LOWER PART OF THE SILO WALL

The lower part of the compartment wall, which is adjacent to the ring beam and the plain concrete on the ring beam, where the fluidslides are located, is not loaded directly with the horizontal pressures from the bulk material. But due to the compatibility of the structure this wall part is also stressed by the material stored above, which causes horizontal tension decreasing from the top of the plain concrete downwards. As already described before, the area, where the inverted cone is supported, will also be tensioned, which means the tension forces are increasing again when approaching to this area. These changing tension forces are caused by changing horizontal deformations of the silo wall, which in turn



Flow channel and pressure distribution (EN 1991-4)



Internal forces in lower part of the silo wall

means bending moments and shear forces in the vertical direction of the silo wall. Combined with vertical compression forces due to dead load and wall friction loads mainly this has to be considered for the wall design.

Equally distributed pressures from the bulk material and high temperatures inside the silo due to hot material stored in the silo will cause horizontal deformations to the outside. The bending moments and the shear forces in the vertical direction will be obviously smaller, if the wall can move without restraint.

This means it is prudent not to provide any connection between the silo wall and the ring beam (including the plain concrete). As described above there are also unequally distributed horizontal pressures on the silo wall, which causes unequal horizontal deformations accordingly and thus an oval shape of the wall mainly with changing deformations to the inside and outside along the wall perimeter. This effect has been observed during measurements at several silo walls.

A horizontal inwards movement of the silo wall will be restricted by the ring beam and the plain concrete on top of the ring beam, which will cause high restraint stresses in this area. In order to reduce these restraint stresses it is recommended to install a

The original IBAU HAMBURG Central cone silo from the structural point of view

soft board between silo wall and the plain concrete with a minimum height of at least 1m and 2 cm thickness. Also post-tensioning of the wall causes inward deformations, which is a further reason for the installation of such a soft board. There have been some severe damages of silo walls in this area in the past, because these movements were neglected and the restraint stresses from a rigid horizontal support were not considered for design.

SILO WALL BELOW CENTRAL CONE

The wall below the central cone is loaded with the complete vertical loads of the structure above. This is one advantage of the central cone silo: All main vertical loads are equally distributed on the silo perimeter and transferred to the foundation. There is no doubt about the distribution of the loads and no difference for loading and discharging. If there are large truck openings below the cone the loads are concentrated beside and between the openings. These areas are comparable to columns and the reinforcement should be provided correspondingly with vertical rebars and enveloping horizontal stirrups.

The wall above the openings is working as a deep continuous beam, which means additional horizontal reinforcement in this area. As already described near the support of the cone high horizontal tension forces will occur, which require concentrated ring reinforcement. This ring reinforcement together with the ring reinforcement of the ring beam has to carry the horizontal part of the thrust from the conical shell. Due to the concentrated horizontal reinforcement openings shall be avoided in this area, at least for 1 m height below the support of the inverted cone. At the support of the cone loads from the upper wall and from the cone are applied on the lower wall. Different loads will cause transverse splitting forces below the cone support, which require transverse ties or stirrups in this area.

LOADS ON THE CENTRAL CONE

A part of the bulk material weight is transferred to the silo wall by wall friction, the remaining part is transferred to the central cone as the bottom of the silo compartment. The inclined surface of the cone is loaded with normal pressures and meridian friction forces from the bulk material due to the vertical and horizontal pressures in the silo compartment.

This causes horizontal and meridian compression stresses in the cone wall. In principle the maximum vertical pressures calculated from the bulk material on the silo bottom result from the load case “filling”. During discharge the wall friction loads will be increased and due to the equilibrium of the total loads the vertical pressures on the silo bottom will be reduced. The resulting loads on an inverted cone are difficult to measure and therefore not exactly known, but corresponding to the loading on a flat silo bottom the load case “filling” can be assumed as governing for the vertical loading as well.

Due to the 2005 edition of DIN 1055-6 the vertical load from the load case “filling” on a horizontal silo bottom had not to be increased any longer with a factor c_b for cement, raw meal, fly ash etc. in order to consider pressure increase due to dynamic effects. But as the uncertainty for the loading on the cone is remaining, it is recommended to increase $c_b = 1.0$ to 1.33.

The discussion still refers to uniformly distributed loads, but as described for the silo wall no uniformly distributed loads will occur in a central cone silo. This was not considered when the first inverted cone silos were developed and for many years the inverted cones were designed with the assumption of uniformly distributed, but increased loads. Nevertheless, the recommended incremental factor can be seen as a factor for considering unequal loads on IBAU Central cones and thus leads to an adequate design result.

Construction guidelines

SILO WALL

Today, the silo wall of a reinforced concrete or post-tensioned silo is normally performed as a slipform concrete structure. This means that a formwork of about 1.2 m height has to be moved upwards continuously with an average hourly rate of about 10 – 20 cm. The rate of concreting and installing of reinforcement has to be adapted to this speed as well as the concrete mix, because hardening of the concrete governs the progress of the slipform procedure. The shape and arrangement of rebars or built-in parts must be adequate for this method, because the place for installing the reinforcement and built-in parts is restricted by the so-called yokes of the slipform.

Slipform concrete needs both – skilled planners and skilled personnel on site, otherwise there will be severe quality problems. During the slipforming procedure a permanent supervision is strongly recommended because there is no possibility for amendments later. If all is done properly the concrete strength is corresponding to a cast-in situ concrete.

There can be minor deficiencies of the concrete cover, which is in contact with the moving formwork. Therefore the bond quality between reinforcement and the enveloping concrete could be reduced. In order to get an adequate safety level the anchorage length as well as the length of lap splices of the rebars has to be increased compared to a cast-in situ concrete.

Due to the normal pressures on the silo wall from the bulk material the horizontal rebars at the inside and outside face of the silo wall are under high tensile stresses, which means the tension lap splices of these rebars are essential for the structural integrity of the silo wall. From tests of such tension lap splices it is a well-known phenomenon, that the capacity of lap splices for large bar diameters is reduced due to splitting stresses in the enveloping concrete. Therefore one measure is proper staggering of horizontal tension lap splices from ring to ring.

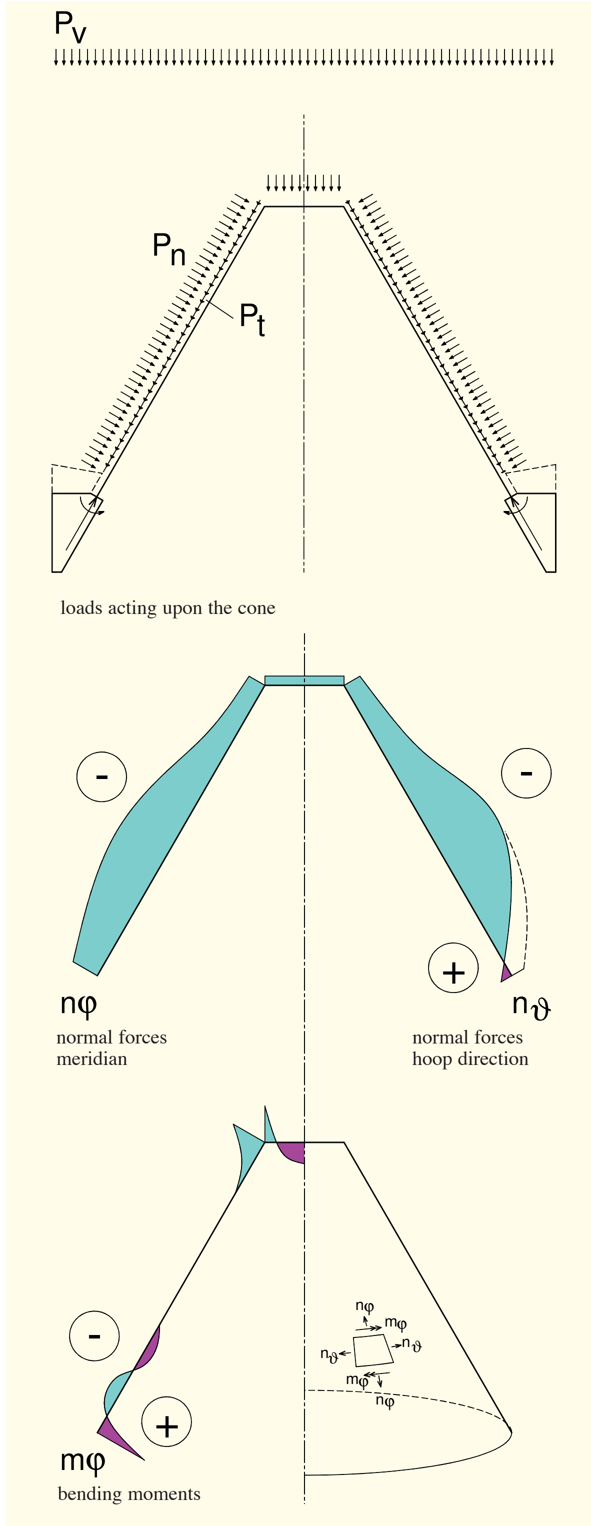
As an additional measure enveloping ties or stirrups have to be provided for tension lap splices of rebars with 16 mm diameter or more. Without such ties brittle failures can occur, which could possibly cause the failure of a complete vertical line of tension lap splices in a wall. This phenomenon is known as “zip” effect and has been experienced from several collapses of silo walls in the past.

The inverted cone is placed on the silo wall on a setback of the wall, which means the lower part of the wall is thicker than the upper. In spite of this change the wall can be executed continuously by slipforming. With proper preparation and skilled personnel it is possible to change the slipform without interruption. Of course all connecting or starter bars for other members will hinder the progress and should be avoided when possible. From the structural point of view there is no connection required between the silo wall and the inverted cone and therefore no connecting rebars should be provided.

For large silos the amount of deformed rebars required for the horizontal tension combined with bending moments will be very high. Due to the slipforming process, which is usually provided for the construction of the silo wall, the amount of rebars, which can be installed per meter of height, is limited. Furthermore, a congestion of reinforcing steel will affect the proper installation and compaction of the concrete. Therefore, it is prudent to provide horizontal post-tensioning for the silo wall of large diameter silos in order to reduce the amount of deformed rebars.

CENTRAL CONE

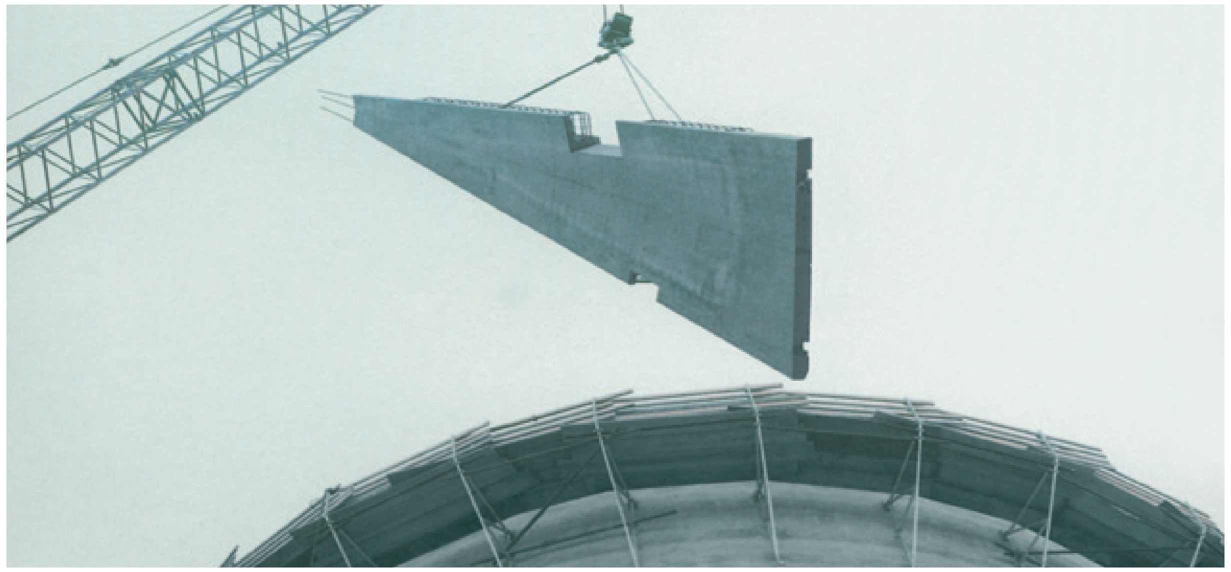
Since the development of the inverted cone some alternative methods have been used for the construction of the cone. In the beginning several cones were performed as a cast-in-situ structure



Principal stresses in the central cone

The original IBAU HAMBURG Central cone silo from the structural point of view

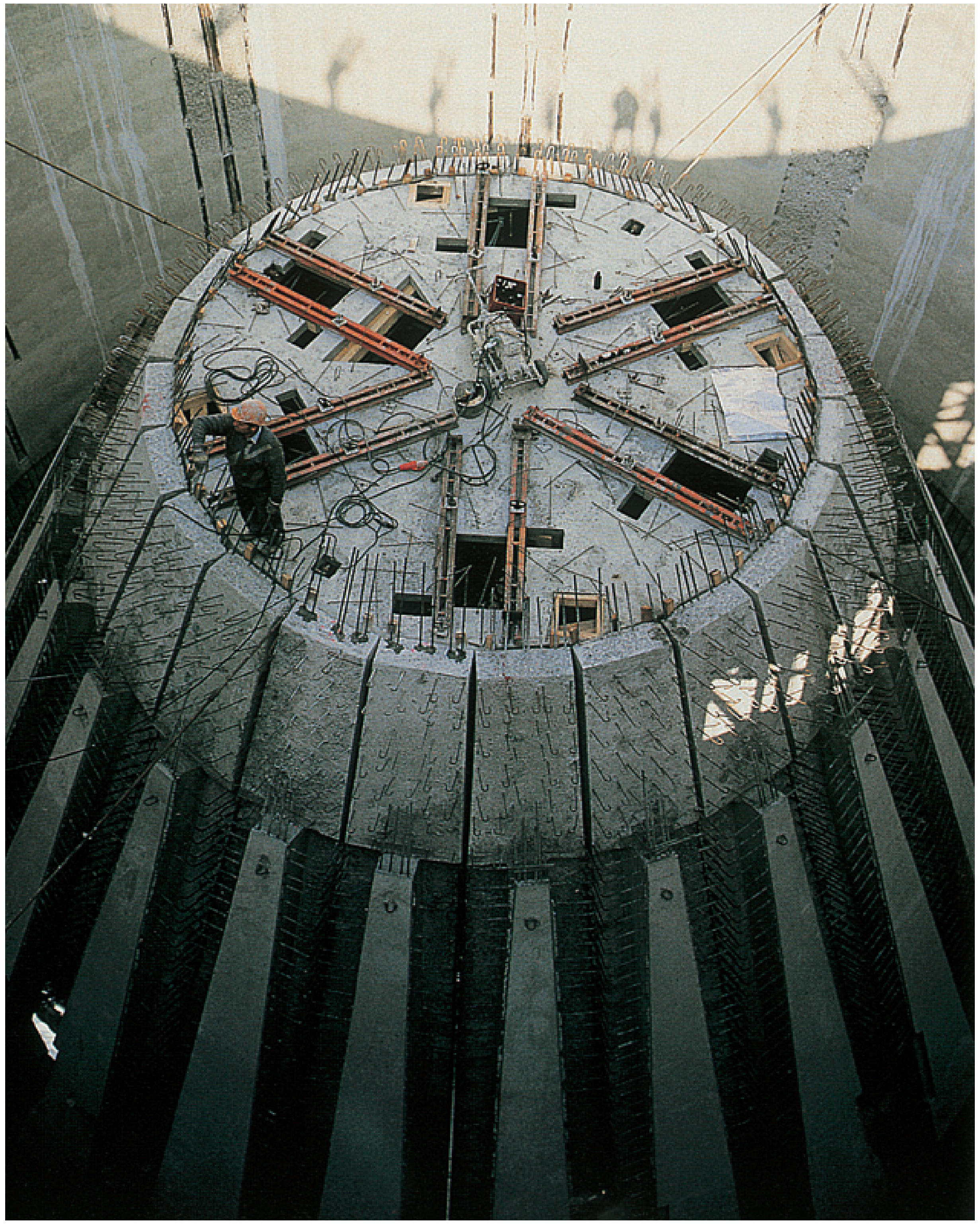
Precast cone segments



Lifting of cone segments

Central cone made of precast cone segments

The original IBAU HAMBURG Central cone silo from the structural point of view



Prefabricated cone for multi-compartment silo

Multi-compartment cone silo

The original IBAU HAMBURG Central cone silo from the structural point of view

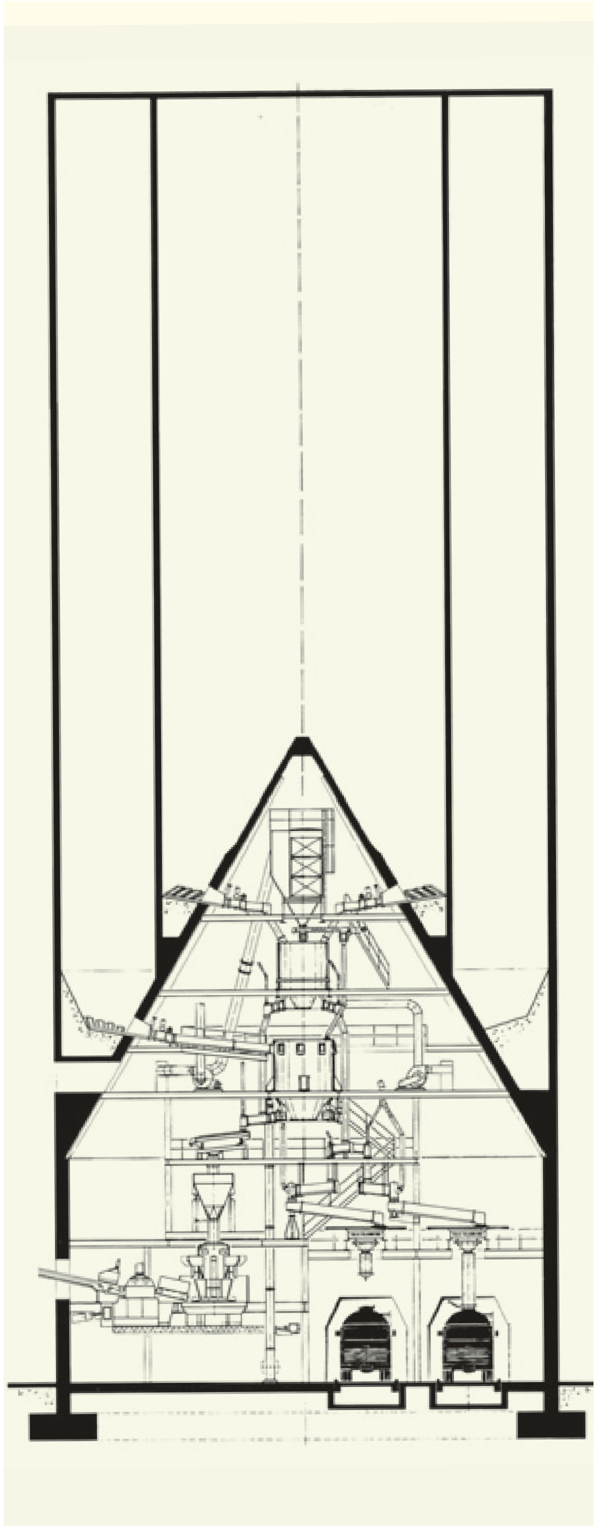
with scaffolding and bottom formwork as well as a top formwork. This is a time consuming construction and therefore other solutions were developed. The most successful method, which is used in the meantime nearly without exception are precast segments with trapezoidal shape in combination with cast-in situ concrete for the remaining joints.

The precast segments cover the complete bottom side of the cone and are placed on the setback of the silo wall. Due to transport and erection reasons the maximum width of such segments is limited to approx. 3.2 m for usual conditions. Most of the segment area has the thickness of the final cone, the bottom part adjacent to the ring beam and the meridian sides have a reduced thickness with rough surface and stirrups protruding from the bottom concrete. The bottom part of the precast segments is the inner formwork of the ring beam, the silo wall is the outer formwork.

The ring beam is a cast-in situ structure, which is joined to the cone segments by connecting stirrups. The meridian sides of the cone with reduced thickness form meridian joints, which are also filled with cast-in situ concrete. Since there is horizontal compression mainly in these joints the lap length of the connecting stirrups can be small. The top side of the meridian joints can be made with formwork panels, which are clamped to the precast segments or expanded metal attached to the stirrups can be used as formwork when using a stiff concrete mix.

Precast segments, cast-in situ ring beam and meridian joints as well as a top slab form a complete composite reinforced concrete structure, which can be constructed within much shorter time than a complete cast-in situ member. Because the segments are produced in a flat horizontal form, the resulting cone structure has a polygon shape in plan, which must be considered for the geometry of the steel floors, which are suspended from the cone, that does not affect the bearing capacity of the structure.

For the first inverted cones made with precast segments scaffolding towers placed in the silo centre were used, supporting the segments near the top. This solution was followed by suspension members fixed at the silo wall and supporting the segments near the top. Though the installation of rebars is hindered by the suspension members this solution is preferred by most contractors nowadays. For large truncated cones, where a formwork is needed for the top slab, the use of a scaffolding tower still remains a useful option. Depending on the weight of segments, height of



The IBAU Ring silo design

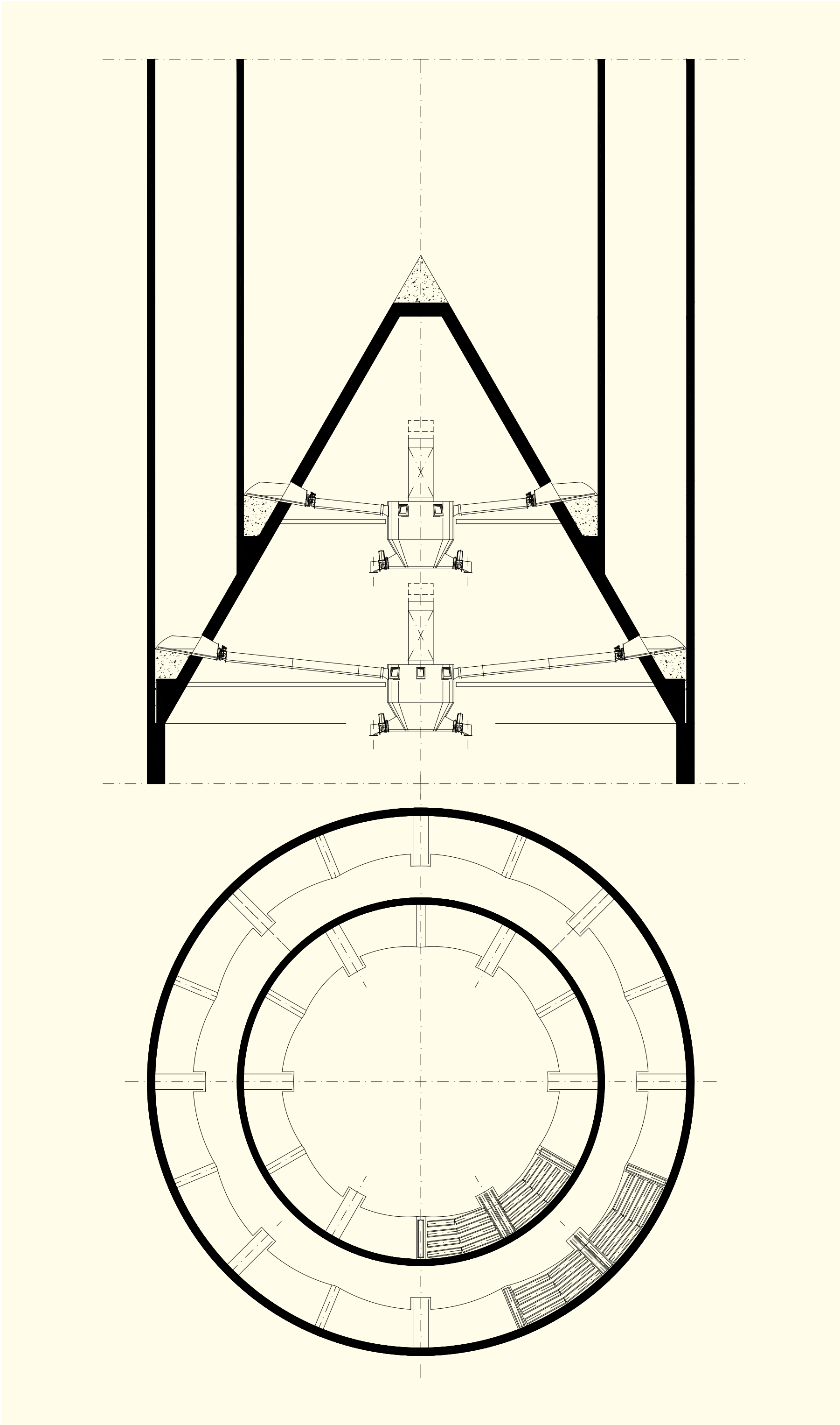
the silo wall and availability of heavy cranes the cone segments can be lifted over the top of the of the silo wall. Alternatively the slipform procedure of the wall can be stopped approximately at the level of the cone top, which makes the construction of the cone much easier, but needs two slipform phases.

Another solution, which has been used by some contractors, is a bottom scaffolding and formwork, where the concrete is installed as a so-called shotcrete or sprayed concrete. Due to several construction deficiencies this method was not really successful and is not recommended.

MULTI-COMPARTMENT SILOS

The central cone silo with a single circular compartment was very successful from the beginning of its development. One of the reasons was the very robust performance of the cone structure as a silo bottom with a very high bearing capacity. Therefore, the transformation of a circular single cell section into multi-compartment silo sections was the next logical step.

The conical shell is able to carry ring loads in plan as well as meridian loads with compression forces mainly combined with some bending moments, which do not affect the cone structure. Therefore, the inverted cone will not restrict the



The IBAU Ring silo design

The original IBAU HAMBURG Central cone silo from the structural point of view

division into several compartments. The silo walls are the governing criterion for an economic and reasonable division. One of the first requests from the clients were two compartments. A division of a circle by a straight wall through the centre of the circle needs an enormous amount of concrete and reinforcing steel for usual silo diameters. Only for silo diameters < 10 m such a solution would make sense.

Therefore, as an alternative the so-called ring silo was developed with two concentric circular walls, which form an inner circle and an outer annular cell. Because the pressures in the outer annular cell = ring depend on the width of the gap, the horizontal wall pressures on the outer wall are much smaller than for a single cell, where the pressures depend on the radius.

As the DIN 1055-6 excludes specifications for ring silos, modifications in the formulas of the code should be adopted with the following recommendations:

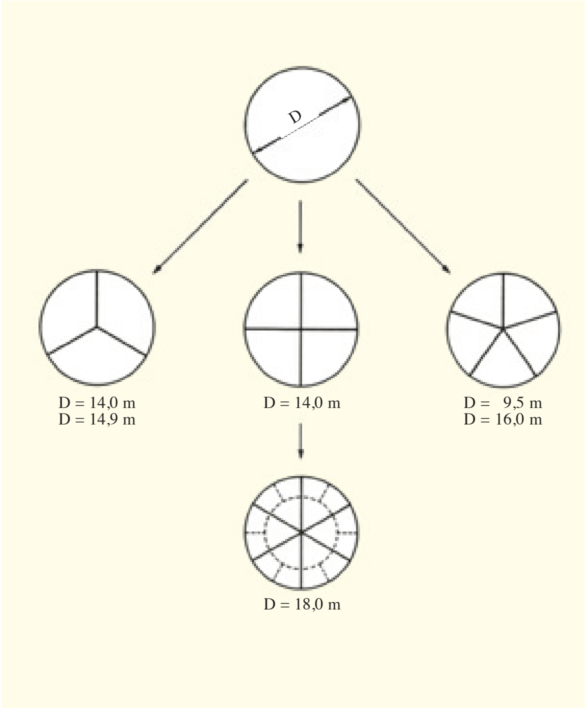
- Uniformly distributed loads from the bulk material can be calculated with the ratio A / u = b / 2,
- A = cross section area of the cell
- u = internal perimeter of the cross section
- b = width of the annular gap

None uniformly distributed loads can be calculated with a modified patch load; the size of the patch load should refer to the outer silo diameter and the inner silo wall should be neglected; the patch pressures can be deducted from the uniformly distributed loads. A combination of these load assumptions has been used successfully for many ring silos in the past. Further comparisons to calculations with an inclined surface of the fill in the silo along the wall perimeter, which were intended to represent the discharge from one opening for a long time, have shown good congruence.

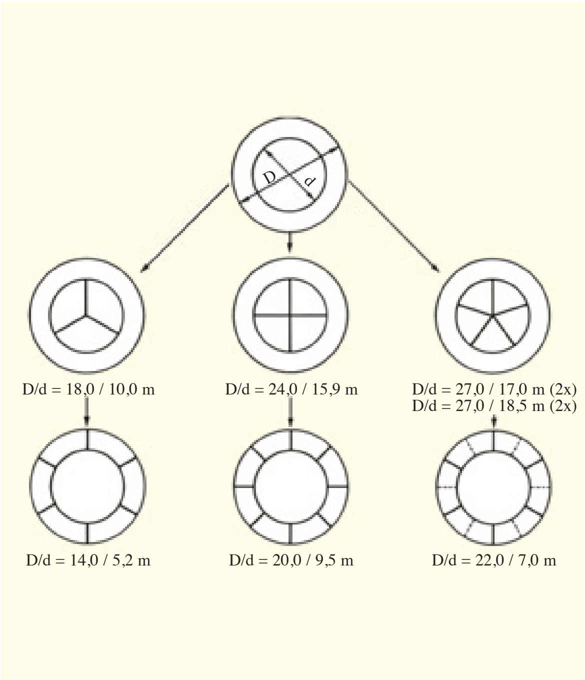
According to the flow channels in the case of large eccentric discharge, it is prudent to assume similar flow channels in a ring silo as well.
As a recommendation the diameter of the flow channel should be adapted to the width of the annular gap. The pressure pattern should be gained according to a silo cell with the diameter of the outer wall and without considering an inner cell.

Another possibility for a multi-compartment division is separating a circular cell by radial diaphragm walls. For small diameters 3 cells are possible, for large diameters a minimum of 4 diaphragm walls should be used. For an economic design the following recommendations should be considered:

- The cross section of a single cell should be as close to a circle as possible



Multi-compartment silos evolved from the circular-cylindrical single cell silo



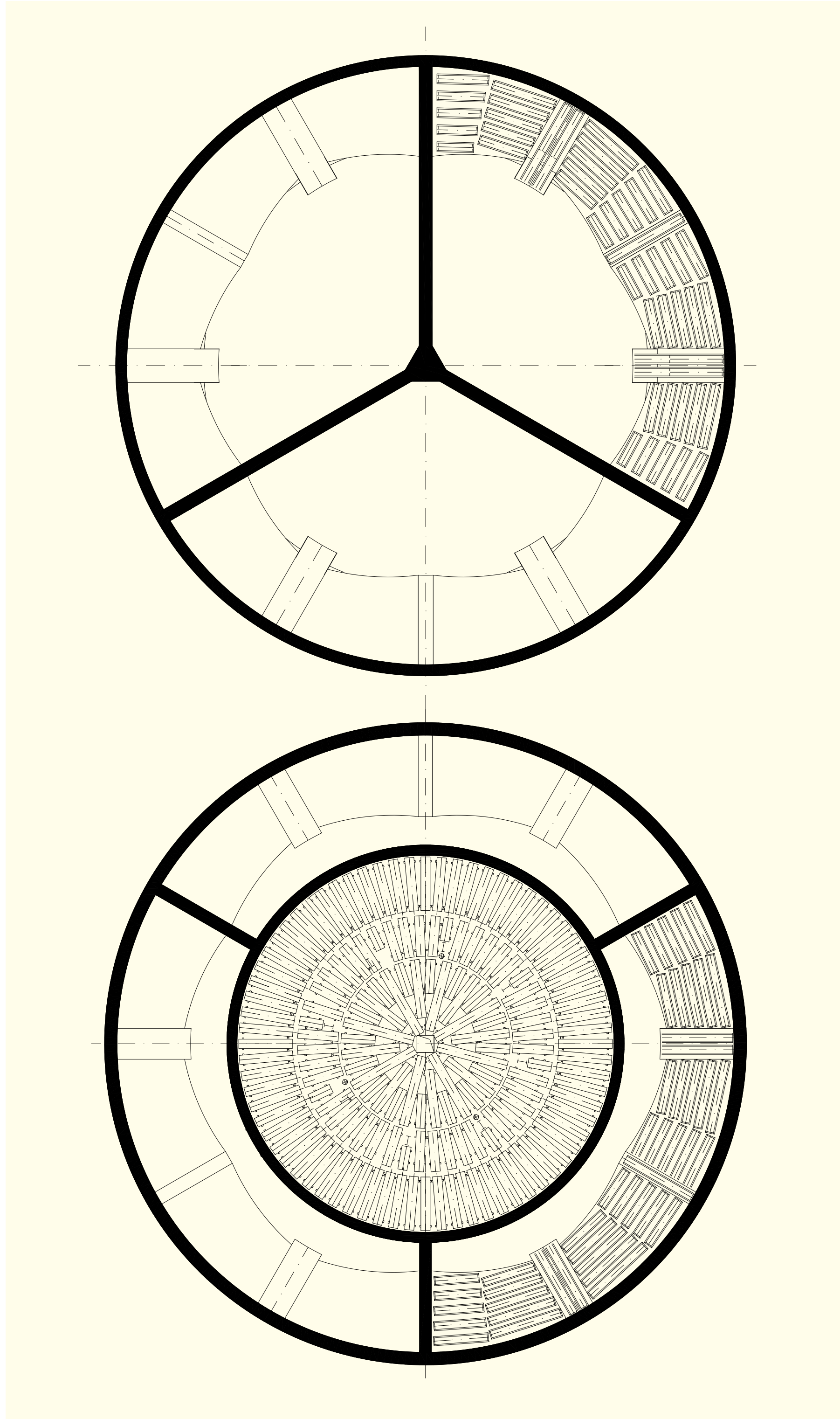
Multi-compartment silos evolved from the ring silo

- The diaphragm walls cause restraint moments at the intersection with the circular wall. Therefore the circular wall should be strengthened in this area by increasing the wall thickness with a chord-like section. The end of the diaphragm wall should be strengthened by triangular fillets (haunches).

Combining the ring silo concept with the radial cell design, the annular cell of a ring silo can be divided by diaphragm walls into several cells as well as the inner circular cell. This can be done for the inner and outer cell simultaneously or for one of these cells only. In case diaphragm walls will be provided inside and outside simultaneously, the pattern of the walls should be adapted preferably in this way, that inner and outer diaphragm walls are in one line. This will reduce bending moments and restraint stresses in the walls and allow a better installation of rebars during the slipforming process.

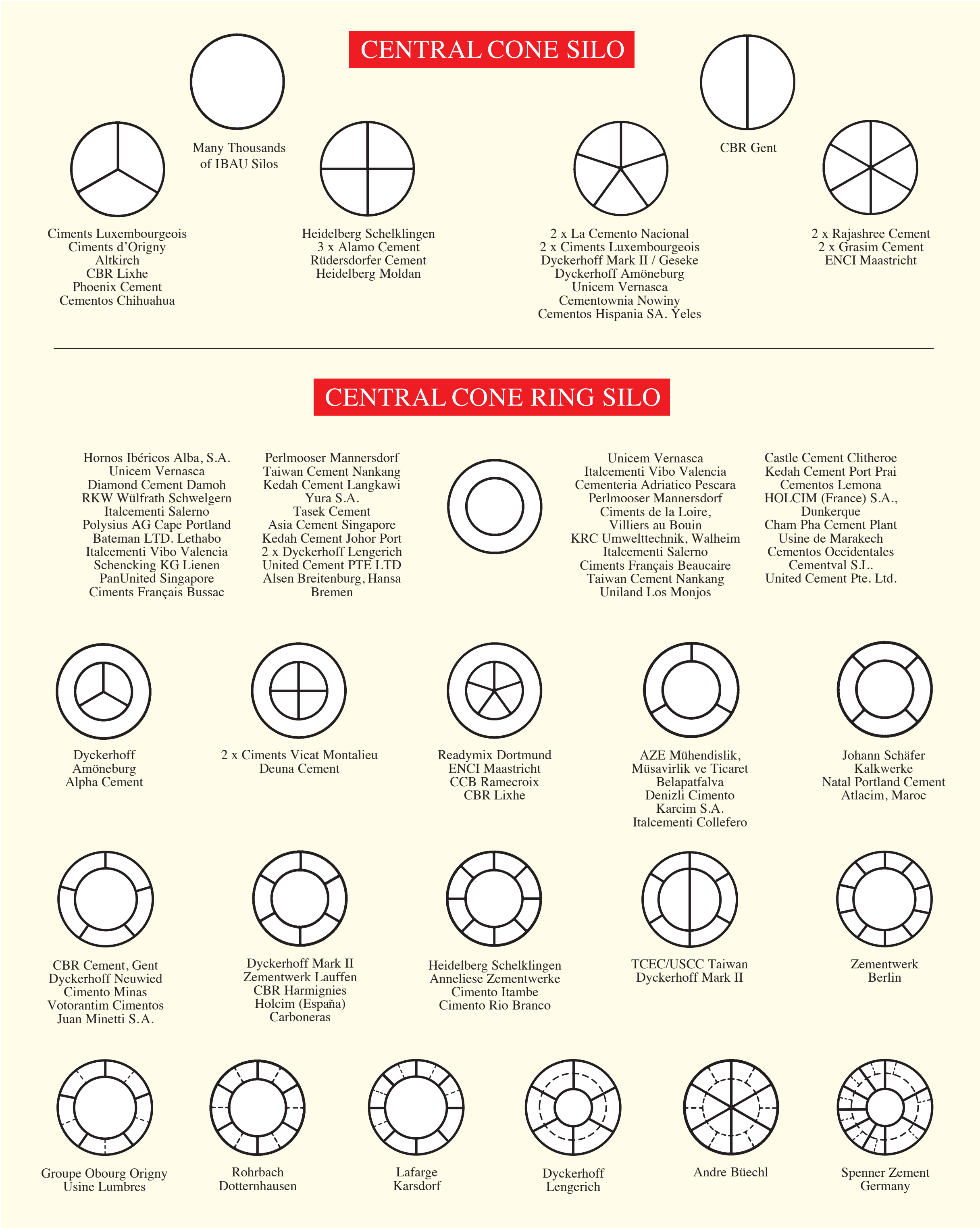
The construction of a multi-compartment silo with inverted cone can in principle be done according to a single cell silo. But there are some modifications required due to the more complicated construction sequence:

- The outer wall and the inverted cone of a ring silo can be performed in the same way as for a single cell silo and the inner ring wall can



Two examples of multi-compartment silo designs

The original IBAU HAMBURG Central cone silo from the structural point of view



Multi-compartment silos evolved from single cell and ring silo, references dated Jan. 2008

be added by a separate slipforming process. The main advantage is the protection of the work inside from environmental influences, but a disadvantage is the lifting of all building materials over the top of the outer wall, which has been finished before.

- Therefore preferably the outer wall is constructed up to the top of the cone. Then the cone is made as described for the single cell silo. Following this the base ring of the inner wall at the intersection with the cone can be constructed. Now slipforming of the inner wall can follow. If there are enough skilled workers and enough crane capacity, inner and outer wall can be built simultaneously.

Summary

With regard to the silo body there is worldwide no silo system which is more economical than the IBAU HAMBURG Central cone silo. A proof for that are more than 7,000 silos with diameters ranging from 10 to 30 m.

In case of a silo with diaphragm walls, which are connected to the outer circular silo wall the following adaptation is required:

- The part of the diaphragm wall, which is connected to the cone, cannot be built with a slipform, but must be constructed as cast-in situ concrete. This means, in a first step the outer wall must be approximately built up to the top of the cone. The shape of the wall in plan above the ring beam must be adapted to the final shape of the wall including thickening at the intersections with the diaphragm walls.

  Starting from the ring beam up to the top of the cone horizontal starter bars with couplers for the diaphragm walls have to be provided.

- The construction of the inverted cone is according to the cone of the single cell silo, but as an additional measure starter bars for the diaphragm walls have to be provided. Depending on the division of cone segments and diaphragm walls these starter bars are placed in the segments or in the meridian joints in between the segments. After finishing the cone the lower part of the diaphragm walls has to be added as a cast-in situ member.

  Now the outer wall, diaphragm walls and cone are ending at the same level with the vertical starter bars for the section above protruding from the construction joint.

- Following this the slipform for the diaphragm walls has to be connected to the slipform of the outer wall and the complete multi-compartment section can be performed simultaneously.