CEMENT - THERMAL POWER - MINERALS

Central Cone Silos
- Single silos.
- Ring silos.
- Multicompart-ment silos.
- From 2 to 22 chambers, diameters: 14 to 27 m.

Marine Cement Terminals
- Floating terminals.
- Mini terminals.
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The original IBAU HAMBURG Central cone silo from the structural point of view

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 multicomartment 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 original IBAU HAMBURG Central cone silo from the structural point of view
Flow channels in an IBAU Central cone silo

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

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 depressurization 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 emptying rate of the silo is more than 99%.
The original IBAU HAMBURG Central cone silo from the structural point of view

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.

**A**

Original IBAU HAMBURG Silo

Ø from 10 - 30 m

Calculation example for a silo diameter of 26 m

- max. 166 kg/s
- 0,03 m² opening per flow control gate
- 2 x bulk loading:
  - 2 x 220 t/h
- 1 x packing plant:
  - 1 x 160 t/h
- max. 166 kg/s
- total discharge capacity 600 t/h

**B**

Silo with depressure chamber

Ø limited to 14 m

Calculation example for a silo diameter of 26 m

- max. 166 kg/s
- 1 m² opening each
- dedusting 4 m/s rate of flow
- 2 x bulk loading:
  - 2 x 220 t/h
- 1 x packing plant:
  - 1 x 160 t/h
- max. 166 kg/s
- total discharge capacity 600 t/h

The original IBAU HAMBURG Central cone silo is used for diameters between 10 m and 30 m.
The original IBAU HAMBURG Central cone silo from the structural point of view

Information

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

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
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 meridional compression forces to the supporting wall, where they are mainly acting in the vertical direction. The redirection of meridional 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 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 I B A U HAMBURG Central cone silo from the structural point of view

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 no 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 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 counteracts 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 uniformly 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 means bending moments and would need very high vertical direction of the silo wall. Combined with vertical compression forces due to dead load and wall friction loads making this 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 (mill with plain concrete). As described above there are unequally distributed horizontal pressures on the silo wall. Because of unequal horizontal deformations according and thus an oval shape of the wall mainly with changing deformations to the inside and plain concrete 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 inverted cone should be envisaged. The concrete with a minimum height of at least 1 m and 2 cm thickness. Also post-tensioning of the wall causes inward deflection of the wall. Another 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 wall and transferred to the foundation. There is no doubt about the distribution of the loads and discharging. If there are large truck openings below the cone the loads are radiated towards the opening. These areas are comparable to columns in the silo compartment. The inclined surface of the cone is loaded with hoop and meridian forces. hoop and meridian forces are essential for the silo wall. From tests of such tension lap splices it is a well-known phenomenon, that the capacity of lap splices or large bar diameters is reduced due to splitting stresses in the enveloping concrete. Therefore one measure is proper staggering of horizontal ten- sion lap splices from ring to ring.

Slipform concrete needs both - skilled planners and skilled personnel on site, otherwise there will be severe quality problems. During the slipforming process, 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.

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.
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

The IBAU Ring silo design

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 concrete, the silo wall is the outer formwork.

The ring beam is a cast-in situ structure, which is joined to the cone segment 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.

The IBAU Ring silo design

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 silo wall and availability of heavy cranes the cone segments can be lifted over the top of the silo wall. As a result of this method was not really successful and is not recommended.

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 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.

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

- 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 the 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 slipping forming 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

As the DIN 1055-6 excludes specifications for ring silos, modifications in the formulas of the code should be adapted 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.
The original IBAU HAMBURG Central cone silo from the structural point of view

Many Thousands of IBAU Silos

I BAU HAMBURG
Central cone silo

Zementwerk Lauffen

2 x Ciments Luxembourgeois

Cimentos Luxembourgeois
Groupe Obourg Origny
Juan Minetti S.A.
Cementos Chihuahua
Usine Lumbres
Cimento Minas
Ciments d’Origny
Amöneburg
Phoenix Cement
RKW Wülfrath Schwelgern
Polysius AG Cape Portland
Italcementi Vibo Valencia
CBR Lixhe

CENTRAL CONE SILO

CENTRAL CONE RING SILO

Our secret is ... EXPERIENCE
- 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.

2 x La Cornue National

Dyckerhoff Mark II

Bedachung Scheidungen

Dyckerhoff Mark II

2 x Ciment Luxembourgeois

Ciments Luxembourgeois

2 x Regenbogen Cement

EnCI Mainz/Rotthar

Schenck Görtelmeyer

Ciments Français Beaucaire

Many Thousands of IBAU Silos

Illustration of the slipforming process

I BAU HAMBURG
company and so expertise of the design local guidelines or the for any changes in the guidelines or to give note on such changes. Accordingly, this brochure is not intended as a replacement of local guidelines or the replacement of the expertise of the design company and so IBAU HAMBURG cannot be held responsible for any claims from using these documents.

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