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A Post-Stressed Concrete Silo to Store 30,000 t of Cement

B.H. Anstey and H. Jensen, Australia

Ein Spannbeton-Silo für die Speicherung von 30.000 t Zement
Un silo en béton renforcé pouvant recevoir 30.000 tonnes de ciment
Un silo de hormigón postensado para almacenar 30.000 toneladas de cemento

セメント30,000トン貯蔵用ポストストレストコンクリートサイロ

计划存贮 3 万吨水泥的后张混凝土 地下仓

صومعة من الخرسانة لاحقة الاجهاد لتخزين ٣٠٠٠٠ طنا من الأسمنت

Summary

The paper describes important pre-design, design, tendering and construction aspects of a single cell 30,000 t cement silo owned and operated by Adelaide Brighton Cement Limited and located on a wharf in Port Adelaide, South Australia. All elements of the structure are discussed and particular emphasis is given to those factors which determine the design of the silo wall and the outloading cone. Reference is also made to current European practice in the design of large cement silos.

1. Introduction

The export of cement in the form of clinker has been an important part of the trade of Adelaide Brighton Cement Limited (ABC) for a number of years. This trade has recently been extended to the West Coast of the U.S. and to the Middle East. ABC will soon commence delivery to California of substantial, annual amounts of the more refined product, cement. This cement is required to be of one type only and each shipload will be a maximum of 30,000 tonnes.

Because of the high demurrage cost on ships, it is essential to store a full shipload near the wharf, and to be able to load the ship at a fast rate. It was decided to build the new 30,000 tonne storage facility on the wharf adjacent to the existing clinker shiploader, which was to be modified to handle cement.

The silo project was developed and implemented by the Group Engineering of ABC who commissioned Consulting Engineers, Macdonald Wagner & Priddle Pty. Ltd. to undertake design, supervision and contract administration of all civil engineering works.

2. Preliminary Studies

An earlier study had shown that a single-cell concrete silo is the most economical form of large cement storage. Furthermore, it was established that for the founding conditions in Port Adelaide, a height to diameter ratio of approximately 1.4 would optimize the structural cost per tonne stored.

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A preliminary design adopted a diameter of 28 m and a height of 37 m for a flat-bottomed silo with a steep conical roof using a relative density of cement of 1.4 to determine the silo volume required to store 30,000 tonnes of cement. Piles would be spaced uniformly over the entire silo floor area.

The diameter of 28 m happens to be the largest possible diameter which the available site can accommodate due to restraints in the form of an existing shiploader, the required clearance to the rail siding and an existing road bridge providing access to docked ships, see Fig. 1.

A cement silo diameter in excess of 15—20 m normally means that a conventionally reinforced concrete wall is both impractical and uneconomical to construct. For these large diameter silos, a concrete wall is only feasible if high strength reinforcement is used.

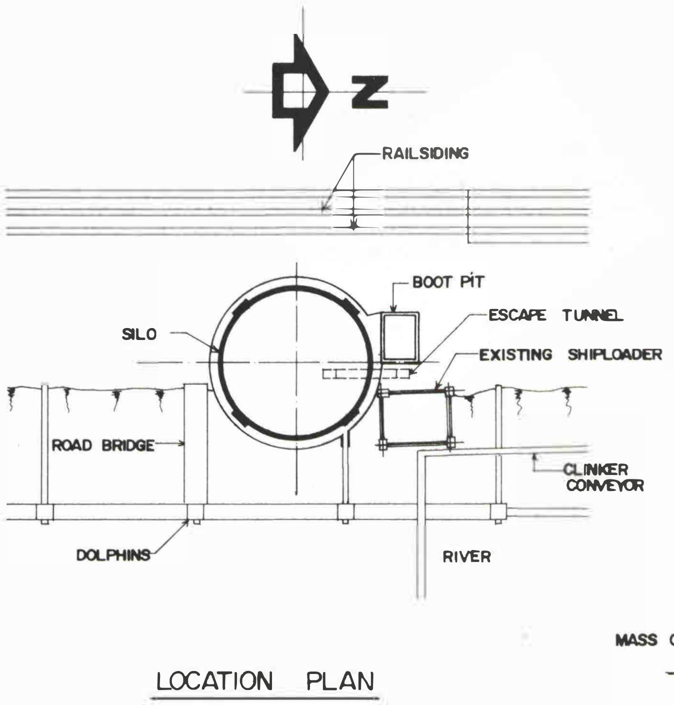
3. European Study Tour

Despite the consultant's extensive experience in silo design, it was considered that because this silo would be one of the largest cement silos in the world, and much larger than any similar structures built in Australia at that time (apart from the 50,000 tonne bauxite silos at Gove), much benefit could be gained from discussions with overseas organisations involved in designing, constructing and operating cement silos. Adelaide Brighton Cement Ltd. has technical connections with a number of European cement groups and advantage was taken of these together with the consultant's own contacts to plan a study tour of Europe, where it was known that a number of very large cement silos had been designed.

Discussions were held with academics, consultants, contractors, cement companies and related equipment suppliers covering all aspects of silo research, design and operation.

The major subject areas covered were:

a) Current research on silo pressures (this has since been well documented in [1]),
b) attitudes towards, and use of, various national codes for the design loads of materials stored in silos,
c) existence of in-house experience which was reflected in design procedures,
d) design approach regarding important details, e.g. full or partial stressing, temperature effects, silo wall-to-base connection,



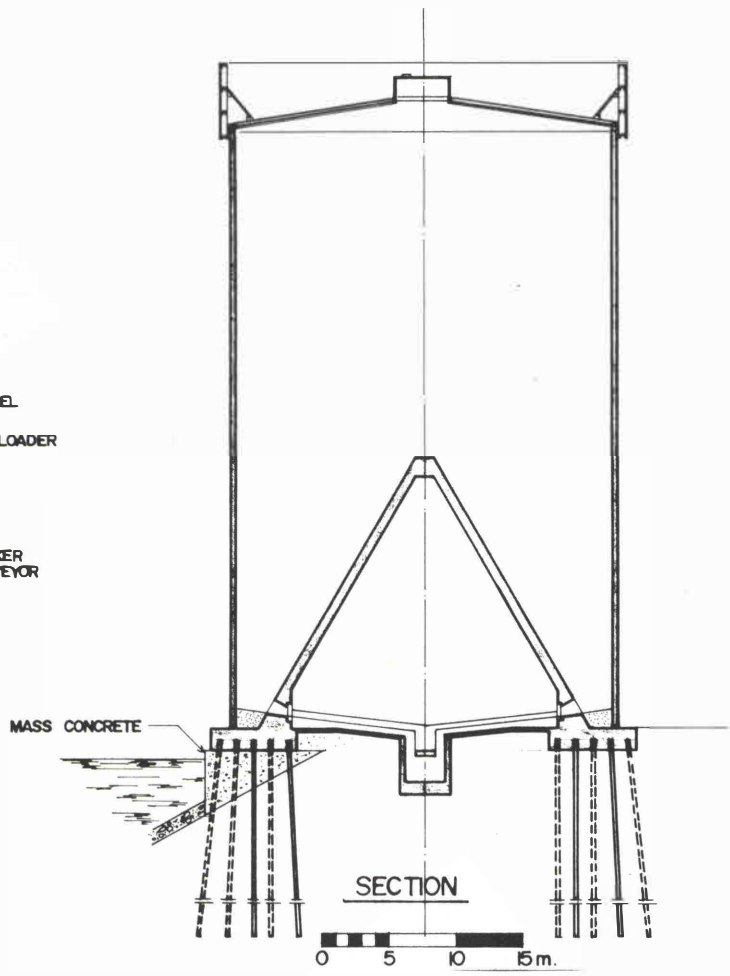


Fig. 1: Location plan of silo installation

e) inloading and outloading methods and the pressures developed during these operations, including methods used to avoid unbalanced loading,

f) construction techniques and their influence on design, and

g) the relationship between technical sophistication in design and the general level of technical development and ability of likely contractors in the country of construction.

The exercise proved to be stimulating and informative. Comments arising from this study tour are included throughout the paper where relevant.

4. General Arrangement

The inloading of cement into the silo is achieved by pumping through a central roof inlet in such a manner as to ensure uniform build-up of the cement surface.

The proper functioning of a cement silo's outloading system is a very important feature of cement storage. The system needs to be reliable in order to achieve a controlled outloading process, and a uniform lowering of the cement surface minimizing unbalanced loading conditions. The system must also be efficient in order to ensure as high a live storage capacity as possible. This will enable the capital cost to be kept to a minimum, it will prevent capital from being unnecessarily tied up in stored material to which there is no access via the outloading system, and it will eliminate the significant cost of the otherwise required regular shutdown periods during which the built-up layers of cement are removed from the walls and floor.

ABC decided to use an outloading system for this silo which has recently been developed and patented by IBAU HAMBURG of West Germany. For this silo, the system consists of a 22 m high 60° cone located on the silo floor concentrically with the silo wall. The distance along the floor from the wall to the cone is about 2 m, see Fig. 2. Twelve evenly spaced outlet openings are located on the circumference of the cone at floor level and an IBAU-patented flow control gate is connected to each of these openings.

The floor between the silo wall and the cone is provided with falls from intermediate ridges towards the outlet openings and with open airslides. Enclosed airslides extend from each flow control gate to the centre of the silo, from which a central, enclosed airslide leads through the tunnel to the bootpit. From here the cement is transported to the shiploader via the elevator and airslide bridge.

During outloading, two opposite flow control gates and their associated airslides are operated simultaneously for a relatively short period of time. When these two gates are shut, the adjacent two opposite gates and airslides are activated. This process continues in a circular sequence to provide reliable and efficient outloading combined with a uniform lowering of the cement surface.

The choice of the IBAU outloading system and the decision to decrease the roof slope to a relatively flat 1:5 changed

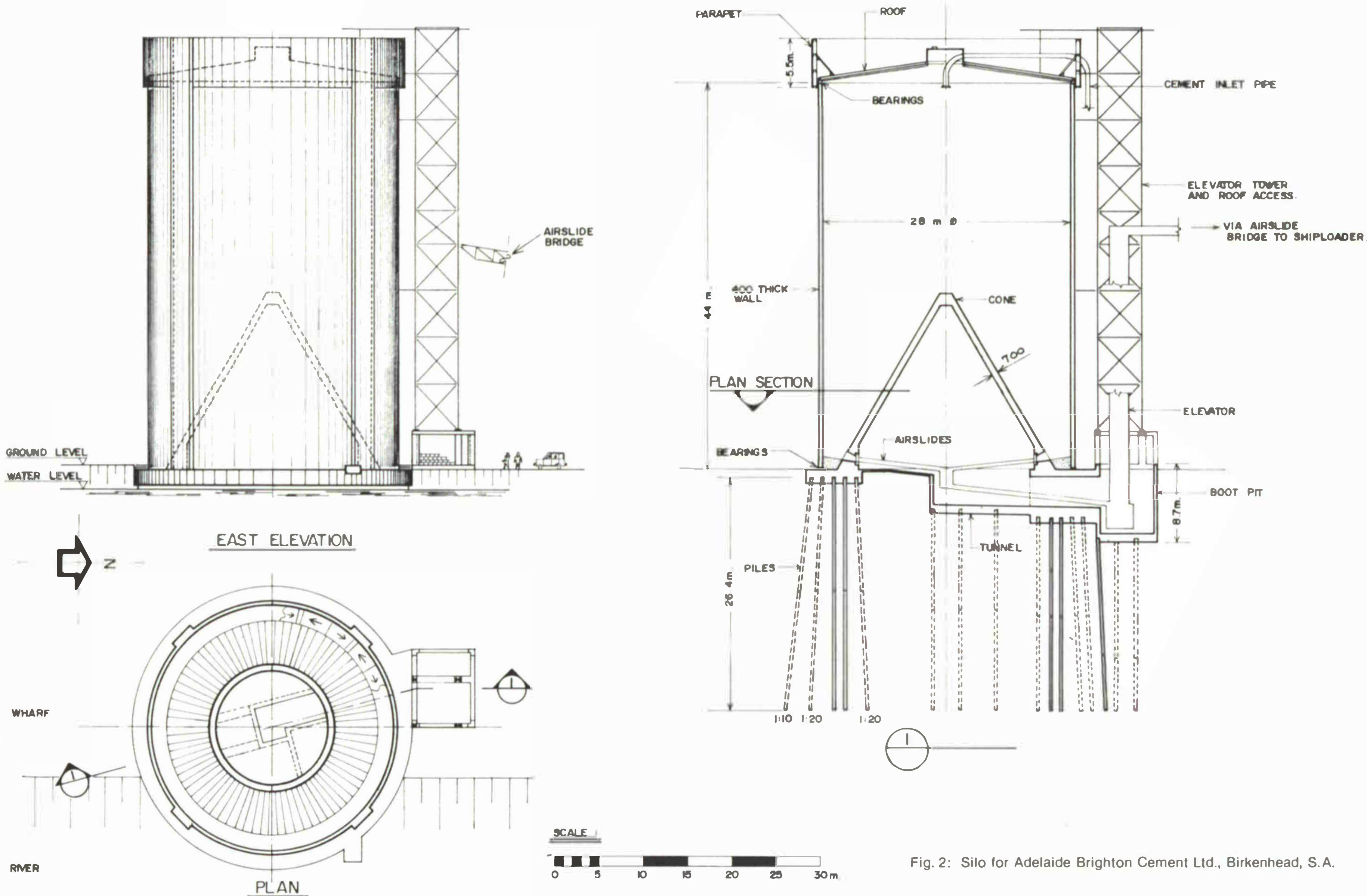


Fig. 2: Silo for Adelaide Brighton Cement Ltd., Birkenhead, S.A.

some of the basic structural layout and dimensions of the preliminary design.

To compensate for "lost" storage capacity within the cone volume and to maintain a desired clearance between the end of the cement inlet pipe and the surface of the cement in the full silo, it was necessary to increase the 37 m preliminary wall height to 44 m.

5. Foundations

All significant structures in the ABC plant are founded on piles, mostly cast-in-situ bulb-type piles with capacities in the 400 to 900 kN range, founded in stiffer clays which occur from 12 to 17 m below ground level. However, due to the extremely high load intensity under the silo (deadload plus liveload is in the order of 450,000 kN) a higher capacity and thus longer pile was required.

The full range of available pile types (steel, in-situ and precast concrete) was considered. It quickly became clear that a dominant factor in pile choice was the minimisation of groundheave caused by in excess of 300 piles at close centres, because of its effect on adjacent wharf and shiploader structures. Sub-soil investigation and pile tests were carried out under the supervision of Ground Test Pty. Ltd. to determine the basis for selection of the type of pile to be used and its working capacity.

The pile adopted was a 310 UC mild steel rolled section, driven to 27 m below ground level, with a working load capacity of 1,500 kN for a minimum centre-to-centre spacing of 1,300 mm. The pile develops most of its resistance in friction over the lowest third of its length.

The most significant parameter in the final design was the minimisation of settlement. The expected maximum long-term settlement for sustained load is not anticipated to exceed 100 mm. To reduce settlement, every other pile in the innermost ring is raked inwards at 1:20 and the two outermost rings of piles are raked outwards at 1:10 and 1:20 respectively.

The inclusion of the cone in the silo results in the transfer of all load from the silo and roof to the foundation through a relatively narrow annulus centred under the wall and cone. The ring-shaped pile cap, which supports the cone and the wall, is 6m wide and 1.9 m deep. This structure, made up of the pilecap ring beam, bootpit, airslide tunnel and the floor slab is basically designed as an integral structure capable of

a) distributing vertical dead and live loads equally to all piles,
b) distributing lateral wind and earthquake loads to all piles in proportion to their relative lateral stiffness, through a fully fixed connection of the piles into the pilecap,
c) resisting circumferential tensions induced by the cone as well as secondary restraining moments caused by strain incompatibility between the compression cone structure and the pilecap ring tension structure and,
d) resisting earth pressures and water pressures including the range of flotation uplifts from varying tidal conditions.

The ring beam structure is designed assuming equal pile loading at any particular section due to the relatively larger vertical flexibility of the piles as compared to the torsional stiffness of the ring beam. The ring beam is designed to accept the range of eccentric loadings possible, dependent upon the distribution of vertical live load between the cone and the silo wall.

The tunnel has been extended in the form of deep beams to span across the ring beam. The number of piles supporting the tunnel and the bootpit has been determined to approximately equalise the positive and negative moments at each position under the extreme loading cases, which are basically the full and empty states. In addition, the bootpit cantilever moment and the tunnel fixity moment have been equated under the extreme loading cases by adjusting both the number and location of piles.

The floor slab is designed as a suspended slab supported by both the ring beam and the tunnel walls.

A steel box section escape tunnel has been provided from the floor slab under the cone to outside of the silo wall. This is designed to act as a ventilation duct if it is found that temperature build-up within the cone becomes excessive.

6. Silo Pressures

There is currently no Australian Standard providing guidelines for the determination of loads exerted by stored material in a silo. Such guidelines, however, are contained in a number of national codes and recommendations by various researchers. Additionally, some large organisations have developed their own in-house design pressure guidelines, which are often not communicated outside that particular organisation. Commonly used overseas national codes include those of the United States, West Germany, France and the Soviet Union. Most design pressure guidelines rely on the classical Janssen formula, which is then modified in several different ways to suit various concepts and conditions.

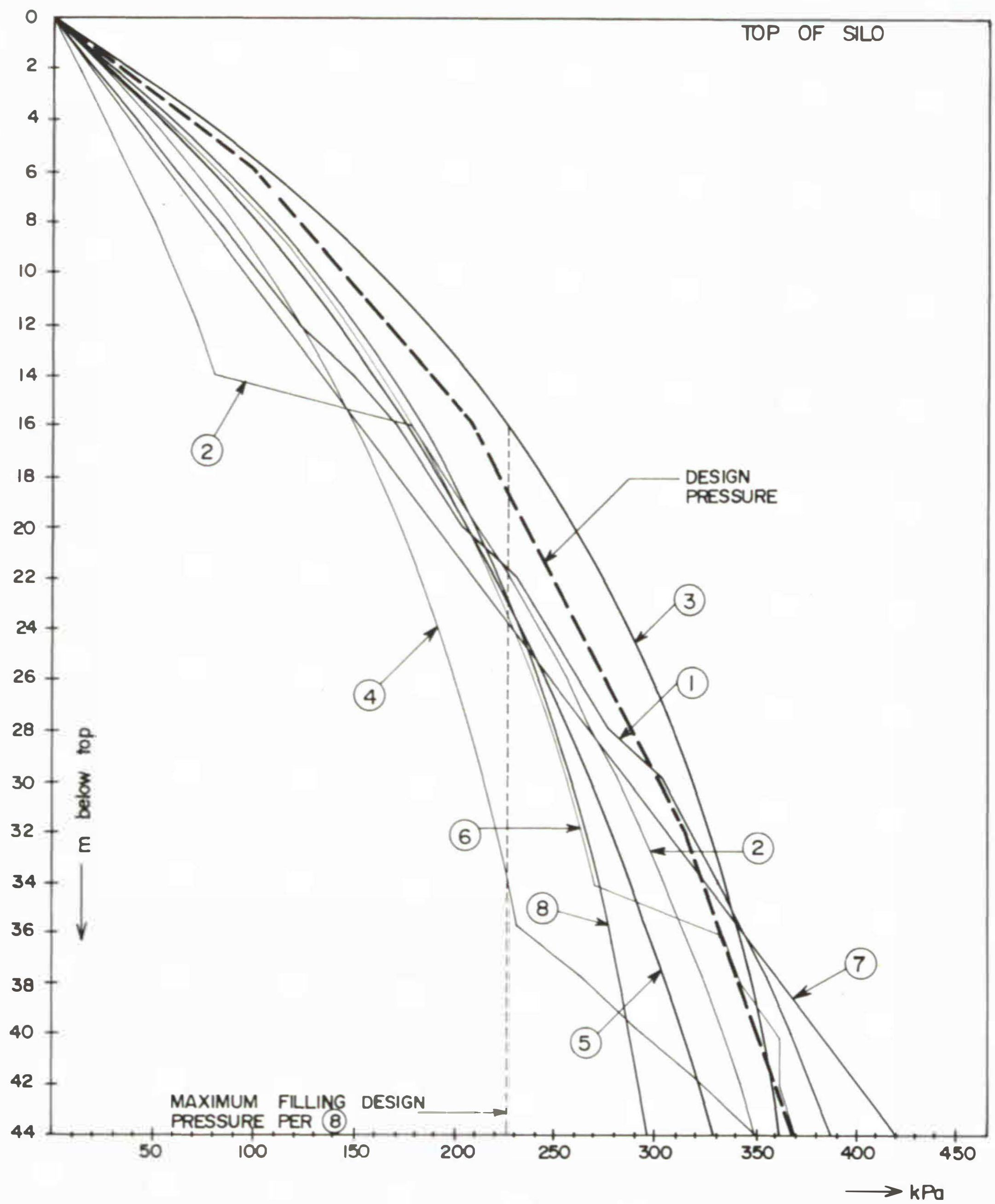
It was found that most European designers used the West German code, including its 1977 update, unless the statutory requirements of the country of construction required otherwise.

A range of codes and recommendations was investigated to compare the various guidelines for the lateral design pressure of stored cement. In each case the particular design parameters of the guideline in question were used to determine the pressure. Fig. 3 shows the lateral pressure of the cement in a flat-bottomed silo of the same dimensions as shown in Fig. 2 in accordance with eight different codes and recommendations as noted. While it is obvious that the authors of the eight design guidelines do not agree on design pressures, it must be noted that not all the guidelines have the capacity to account for phenomena like eccentric discharge and aeration, i.e., the curves shown are not directly comparable. All eight curves represent the pressure during emptying, which normally governs the wall design.

The most comprehensive code is the French, which has the ability to include a range of effects, some of which are neglected or explicitly excluded by other codes as having no effect on the wall design. However, the application of the French code to cement storage is limited to silos for which the hydraulic radius is 6 m or less.

Table 1 shows some of the basic design parameters used in the calculation of the design pressures of Fig. 3.

No literature regarding the effect of the cone on the lateral design pressure appears available. However, it is considered that the cone will not increase the pressures, but will probably decrease them below its apex. This would be due to the induced flow-pattern consisting of a series of "localised"



NA *(1) ACI 313-77 (US CODE)

NA **(2) CH-302-65 (SOVIET CODE)

NA *(3) DIN 1055 - Blatt 6, 1977 (GERMAN CODE)

A *(4) PETER MARTENS, Braunschweig

A (5) R. T. JENKYN

A *(6) RÈGLES DE CONCEPTION ET DE CALCUL DES SILOS EN BÉTON (FRENCH CODE)

A (7) $.6\gamma z$ ($\gamma = 1.6$)

NA **(8) DIN 1055 - Blatt 6, 1964

* Incl. effect of eccentric discharge.
** Excl. effect of eccentric discharge.
NA = No Aeration
A = Aeration

Fig. 3: 30,000 t cement silo — wall pressures

Table 1: Design parameters for lateral design pressure

Code or Recommendation	Relative Density	Angle of Internal Friction	Coefficient of Friction Wall/Cement	Lateral Press. in % of Vertical Pressure
U.S. Code ACI 313-77 [2]	1.6 NA 1.0 A	25 deg.	.40	41 NA 100 A
Soviet Code CH-302-65	1.6	30	.60	33 NA
West German Code DIN 1055-6 1964 & 1977 [3,4]	1.7	20	.36	50 F 100 E NA
Peter Martens Braunschweig [5]	1.55	25	.47	50 F 70 E A
R.T. Jenkyn[6]	1.6 NA 1.3 A	25	.35	121 NA 100 A
French Code No. 189 [7]	1.6	28	.43	48 F 85 E A

Note: NA = No Aeration
A = Aeration
F = Filling
E = Emptying

mass-flows in "sub-silos" of a diameter less than half of the full-silo diameter of 28 m.

A lateral design pressure similar to but somewhat lower than that prescribed by the West German Code, as amended in 1977, was adopted for the wall design, see Fig. 3.

7. Wall Design

Most current design practice consists of fully stressing the wall, i.e., achieving a compressive stress level in the concrete which, even in the long term, will be numerically higher than any tensile hoop stresses induced by the lateral design pressure. However, a design philosophy of "partial stressing" has been adopted to accommodate the hoop tension resulting from the lateral design pressure. The principle of this approach is that the amount of high strength reinforcement is determined in an ultimate state, in which the reinforcement maintains equilibrium with the design lateral pressure using suitable load factors. The high strength reinforcement is stressed to a level which in the long term, i.e., after losses, allows tensile stresses of up to 3 to 4 MPa to occur in the wall under the design loading conditions. These tensile stresses are not considered as having any adverse effects because:

a) The maximum occurring tensile stresses are of a magnitude similar to the tensile stress capacity of the concrete (F'_c = 40 MPa), and
b) the design load occurs only during emptying, i.e., for an extremely short period of time, after which the wall will again be subjected to compressive stresses only. The short periods of time during which very fine cracking could occur, are not considered long enough to result in any unacceptable condition regarding moisture penetration from outside the silo wall. Furthermore, the stored cement, which is hot when pumped into the silo, has a "self-healing" capacity for fine cracking.

The principal purpose of stressing the high strength reinforcement is thus not a strength consideration but a serviceability consideration; in other words the degree of stressing is such that cracking is limited to an acceptable level.

An important advantage of the partial stressing philosophy, as compared to the conventional approach, is that concrete creep is lower because of the lower stress level. This is particularly important in the design of structures like a cement silo which have a high operating temperature and dry environment. The effect of these conditions is to increase concrete creep.

The tender documents were prepared in such a way that any acceptable stressing system available in Australia could be proposed. The successful tenderer has chosen to use the VSL Multi-Strand System with Type 19Sc stressing anchorages.

During the silo wall slipforming operation, empty ducts are placed in the wall at a spacing of between 300 and 600 mm. As soon as possible, i.e., when the wall emerges from the slipform, the ducts are proved by a dolly system to ensure an easy cable insert operation. Four stressing buttresses spaced at 90° are slipformed integrally with the wall. The length of each cable corresponds to 180° of the wall circumference and the cables are installed in a staggered pattern. Each cable is stressed from both ends simultaneously; the stressing sequence of the cables is such as to minimise temporary, differential, radial wall deformations and the resulting secondary moments.

Vertical stressing is not used since it is required neither for strength nor serviceability. Additionally, it is difficult to install and grout vertical stressed reinforcement in a silo of this geometry. European practice is, for the same reasons, to generally avoid vertical stressed reinforcement in this type of silo.

All the secondary flexural effects are resisted by mild steel reinforcement in conjunction with the concrete wall.

The method of joining the silo wall to the foundation determines the vertical bending moments which will occur due to stressing, concrete shrinkage and creep, and loading/unloading of the silo. European practice varies over the range of options from fully fixed to free-to-slide, dependent partly on the designer's philosophy, and partly on the degree of sophistication available in the country of construction. All agree that the free-to-slide condition cannot be considered as permanent.

The free-to-slide option was chosen for the ABC silo. Ninety evenly spaced bearings are positioned in a circle on the top of the pilecap under the wall which they support. Each bearing is designed for a vertical force of 3,000 kN and can accommodate a radial movement of plus or minus 45 mm. The sliding occurs between a stainless steel plate and a rulon-faced steel plate and involves a friction of 4 to 5%.

The anticipated radial movements of the wall relative to the silo centre are as follows:

a) Initial movement due to elastic deformation of concrete during stressing = 8 mm.
b) Additional long term movement due to shrinkage and creep = 21 mm.
c) Maximum movement during emptying = 6 mm.

Although the wall has been detailed to be permanently free to slide, reinforcement has been included to provide for the vertical moments caused by half of b) and all of c) above.

The wall is designed to withstand the secondary moments of two wind load conditions, namely a construction windload corresponding to a 5 year return period using half of the specified F'_c, and a normal windload corresponding to a 50 year return period using the full value of the specified F'_c.

Shear and overturning effects due to lateral forces are governed by a design earthquake in accordance with the Australian Standard AS 2121. The shear is resisted by a combination of friction in the bearings under the wall and a series of tangential reinforcing bars providing full tangential resistance in any direction. The typical shape of these bars is shown in Fig. 4.

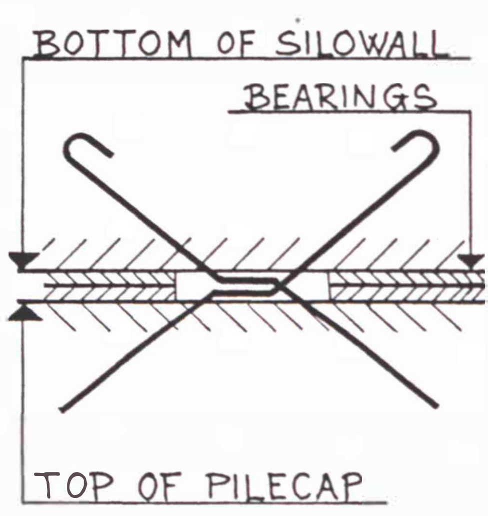


Fig. 4: Elevation of lateral load resisting reinforcing bars

The overturning effect is adequately resisted by gravity loads alone.

A temperature differential between the inside and outside of the wall causes secondary moments which are resisted by mild steel reinforcement placed adjacent to the colder face. The inside design temperature is +100°C, and the outside 0°C. The design temperature differential, however, depends on which design guidelines are used. The philosophy of the US Code, for example, is to design for only a part of the difference between the design temperatures and in addition to take advantage of an insulating effect caused by the stored cement, while the French code prescribes a design temperature differential which is dependent only on the wall thickness and the two design temperatures. The French requirement is the more stringent, and has been adopted above the surface of the cement where no insulating effect is possible. Any of the normally used formulae for the determination of design temperature differentials must be considered as rather empirical due to the non-stationary nature of the heat flow.

The secondary moments caused by the ovalling effect resulting from direct sunshine on an empty silo have been found not to exceed the flexural capacity of minimum wall reinforcement.

Another ovalling effect, caused by a nominal unbalanced load, has been considered in accordance with the French code and results in secondary moments of a magnitude similar to that of moments induced by the temperature differential.

8. Cone

The loading exerted by the stored cement in the full silo governs the design of the IBAU-cone.

The cone is a shell structure which generally is subject to compressive stresses only. To maintain equilibrium at the bottom of the cone, a uniform vertical and a uniform horizontal reaction are required. The vertical reaction is offered by the piles through the pile cap and the horizontal reaction is provided through tensile ring reinforcement. Approximately one-third of the necessary ring reinforcement is located in the lower and thickened-up part of the cone itself, while the pile cap provides the remainder. Due to strain incompatibility at the bottom edge of the cone (compressive "shell-stresses" and tensile "ring-stresses"), rectifying secondary moments are generated. These moments, however, die out very quickly up the side of the cone.

The cone, being 24 m in dia. at the base, and 22 m high, is a large structure in itself. Similar, but smaller cones have been built of structural steel, but the size of this cone makes it preferable to construct it out of reinforced concrete. Consideration was given to precast concrete, but the problem posed by very heavy elements and highly stressed joints made this uneconomic.

It was clear that in-situ reinforced concrete was the most economical form of construction, but three major problems required resolution, viz.:

(i) Should the cone be constructed before or after the wall is slipformed,
(ii) how is the inside face to be formed, and
(iii) should the outside face be formed?

The solution to these problems determines both the construction time and the economy of the superstructure as a whole.

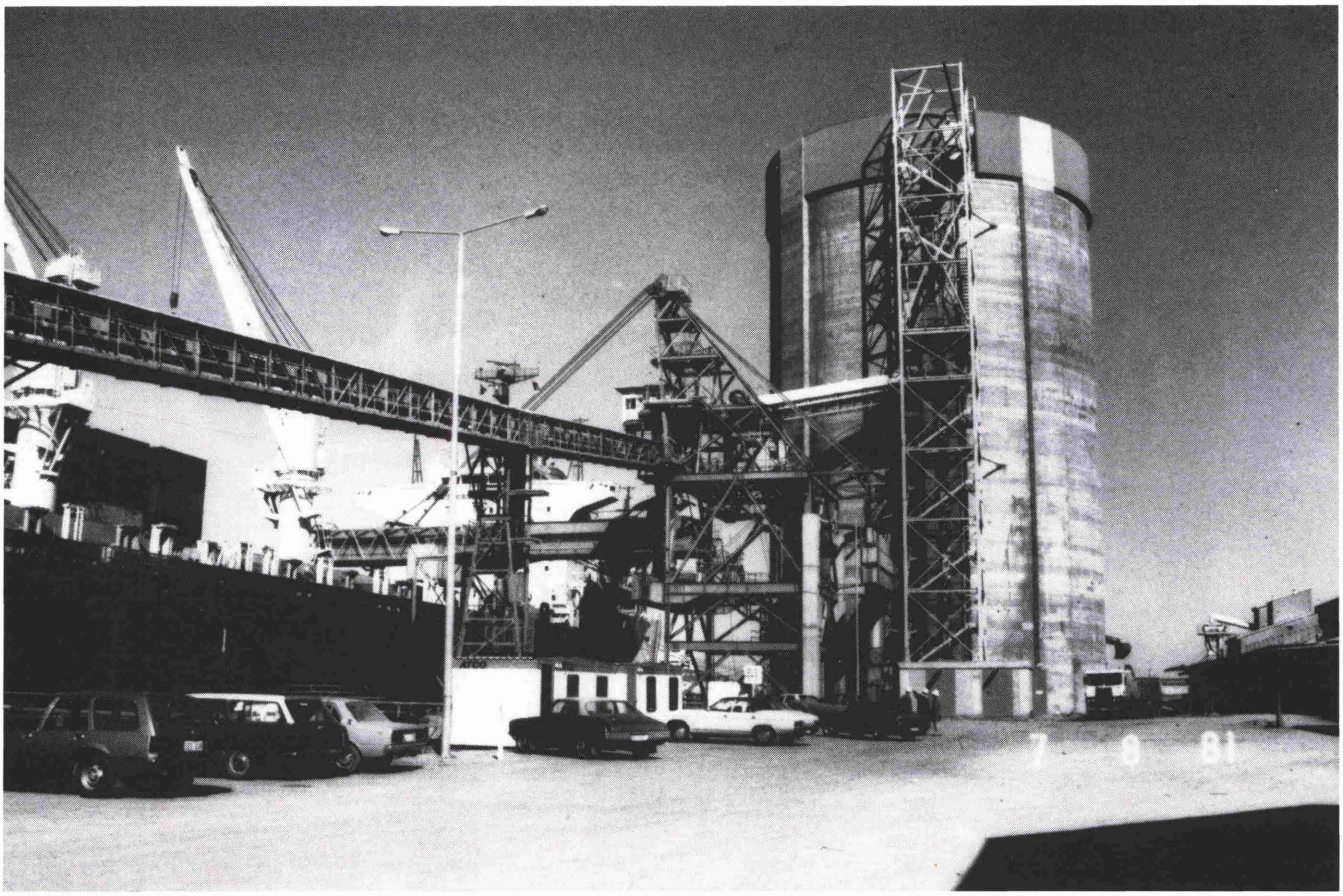


Fig. 5: Cement terminal for loading sea-going vessels

Many different answers to these questions have been tried in overseas projects. At this stage, no pattern seems to be emerging as the solutions are dependent on such variables as size of cone and available technology and labour skills in the country of construction.

On one project the cone was built first, the steel silo roof was erected on top of the cone and then picked up by the moving forms as they rose during slipforming of the walls.

The internal formwork has varied from traditional scaffolding supporting formwork panels, to tapered precast concrete form sections, to permanent steel liners. One interesting technique developed in West Germany consists of the construction, outside the silo and simultaneously with it, of a cone of styrofoam blocks of a size corresponding to the inside of the finished concrete cone. The reinforcement cage is assembled as a unit over the styrofoam cone. A crane then removes the cage, lifts the styrofoam cone to the inside of the silo and positions the reinforcement cage over it. Concrete is applied by shotcreting, and after sufficient curing the styrofoam blocks are removed from the inside via the reclaim tunnel.

It was decided to allow tenderers as much freedom as possible to propose construction methods for the cone, as these methods are determined primarily as solutions to the above construction problems. The four tenderers proposed different forming and concreting techniques as well as different construction sequences regarding the wall and the cone.

The construction sequence selected by the successful tenderer was to slipform the wall and build the cone inside.

The construction method for the cone consists of the erection of inside formwork, fixing the reinforcement from an outside scaffold, and the application of the concrete by shotcreting followed by woodfloating and steel trowelling, to achieve the smooth finish required for the proper flow of the cement during outloading.

A test panel was successfully erected, shotcreted and finished at a very early stage, to confirm the feasibility of the contractor's proposed construction method.

9. Roof

A number of alternative designs using flat and conical shapes in steel and reinforced concrete were investigated. The conical steel roof was chosen because it offers structural efficiency, possible prefabrication in segments (hence minimising on-site construction time), and ease of cleaning and drainage. Steel construction also allows more readily for penetrations for such items as level indicators, access hatch, inspection holes, cement delivery piping and the dust collector, as well as for future modifications to these items.

The roof is designed to slide freely on top of the concrete wall to accommodate relative movements due to wall stressing, roof loads and a temperature differential of 80 °C.

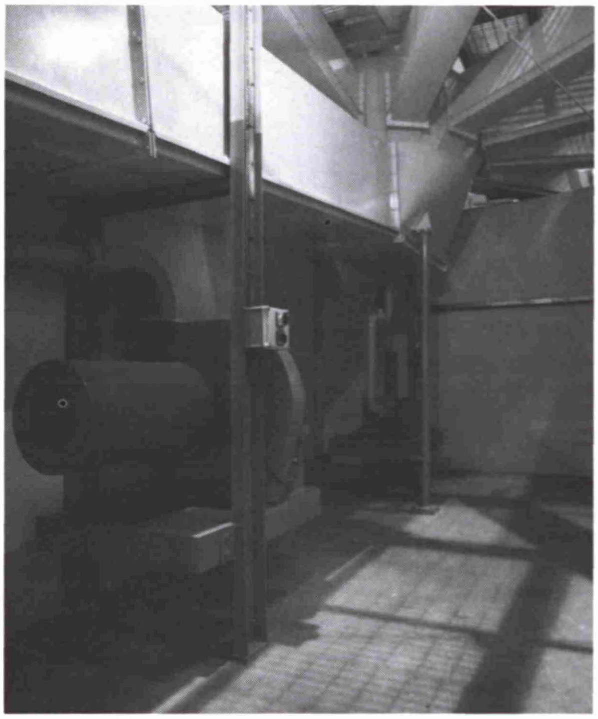


Fig. 6: Central hopper with main fluidslide

ing of cement pumping, and internal pressure due to malfunctioning of the dust collectors.

10. Elevator Tower

The main functions of the elevator tower are to house the elevator (which lifts the cement from the bootpit to the airslide bridge), support the airslide bridge to the shiploader and to provide access to the roof.

The structure is a conventional structural steel tower consisting of four columns and a number of platforms. It is supported by the roof over the bootpit and braced back to the silo wall at two levels.

11. Tendering and Contract Details

In order to enable construction work to commence as early as possible, it was decided to order the steel piles directly from BHP and to divide the work into two contracts, the substructure including piling, pile cap, tunnel and bootpit and the superstructure including silo wall, cone, roof and elevator tower. In this way it was possible to call tenders for the first

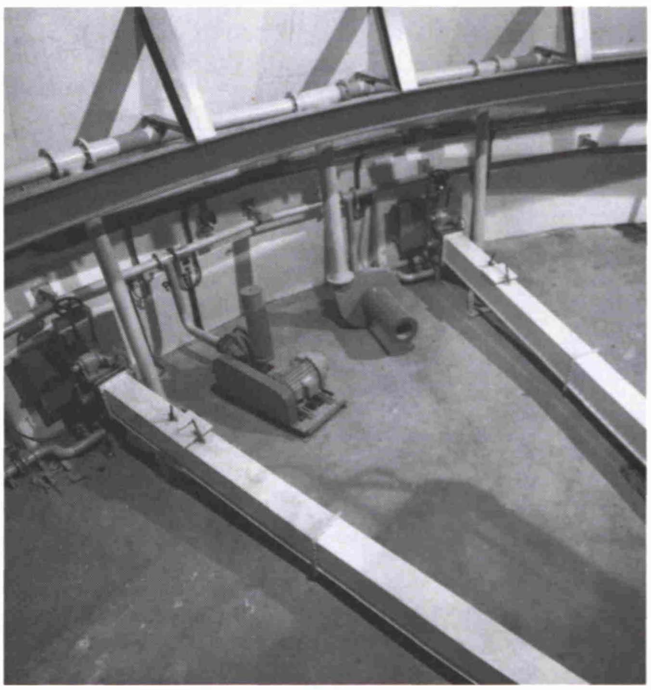


Fig. 7: Discharge openings and fluidslides for the cement transport to the central hopper with the dedusting filter

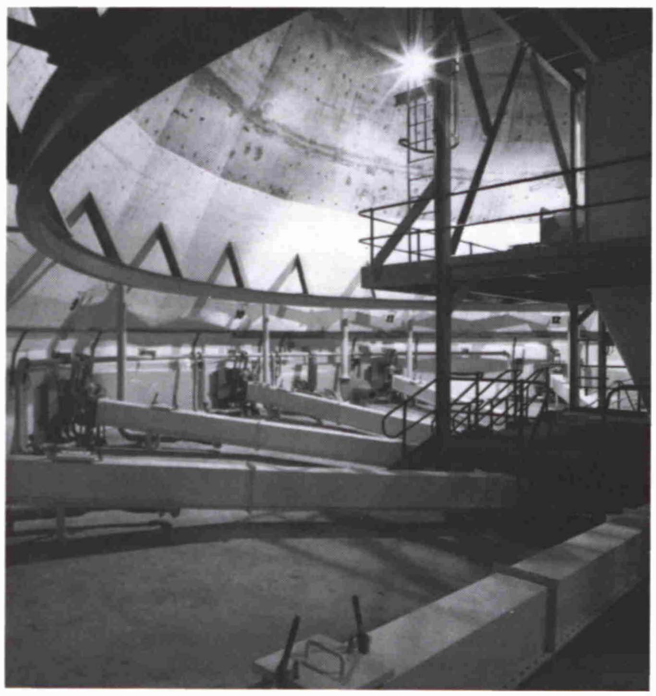


Fig. 8: Two of the 12 silo outlets

Bearings are fitted with rulon on stainless steel for sliding, supported by viblon pads to provide rotational capacity. Silicone rubber dust seals are fitted on internal and external faces of the silo wall, to prevent ingress of atmospheric moisture, cement dust leakage to atmosphere and clogging of the sliding bearings.

Apart from nominal wind, live and equipment loads, the roof is designed to withstand internal suction due to malfunction-

contract simultaneously with the commencement of the final detail design and documentation of the work covered by the second contract.

McMillan Contracting Pty. Ltd. of Adelaide won the substructure contract, and Allied Constructions Pty. Ltd. of Wollongong, New South Wales, won the superstructure contract.

Acknowledgements

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