Discussion

Mr Leopold Brook introduced the Paper, in the absence of the Author, with the aid of a series of lantern slides.

The Chairman said that the Author was right in emphasizing the importance of foundations, because silos were among those rare structures which were frequently loaded to their full design load; in most cases relative settlement was what mattered and not absolute settlement. Fortunately, silos were a type of structure which could itself often be utilized to redistribute foundation loads and so reduce relative settlement. Care was not always taken with the foundation. A silo at Algiers had failed completely by sliding on a circular arc—there was a picture which showed it leaning over at about 45 degrees.

Could the Author give more guidance on wall thickness? In the Paper 5 inches was mentioned as a reasonable thickness. How did the Author select a thickness and reinforcement to make a wall weather-tight?

With regard to formula (3), was the horizontal pressure p_1 always the active or minimum pressure? In deeper silos it might be considerably more.

In the Paper, timber was dismissed because of its low tensile strength. The Chairman suggested that it was not a question of low tensile resistance; the tensile strength of timber was quite good, but old-fashioned methods of jointing timber in tension were extremely weak. He thought that modern laminated technique might offer some interesting solutions in the construction of silos. Reference was made in the Paper to abrasion, and abrasion might put timber out of court, but it should be possible to design satisfactorily a silo in timber, so far as strength was concerned.

He agreed with the Author that reinforced-concrete structures had an unduly bad name for difficulty of alteration. It was often quite as difficult to alter a steel structure as it was to alter a reinforced-concrete structure.

Mr F. S. Snow, referring to the statement made in the Paper regarding the short life of timber and particularly to its lack of fireproof qualities, said that there were some 50-foot-high silos built of timber at Trafford Park, which had been bombed and had caught fire, but they had never actually burnt out; once the timber had charred for $\frac{1}{2}$ inch on the outside, the remainder of the timber remained intact. There was a tendency, especially where thick timber was used in large sizes, to over-emphasize the fact that it was affected by fire.

Had the Author utilized steel formwork in the sliding formwork for the shutters completely, instead of timber, and, if so, what were the advantages or disadvantages of steel formwork compared with any other?

Assuming that the sliding formwork had been constructed about the silos, then when the form was moved upwards there would be considerable distortion in the formwork caused by the heat and the water in the concrete

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those forms might distort as much as 3 or 4 inches in any direction. Moreover, in jacking up it would be found that the forms had a tendency to twist, so that, starting with a 5-inch wall, the thickness might become $3\frac{3}{4}$ inches in one place and $5\frac{3}{4}$ inches in another. To overcome such difficulties, a triangulated set of tie-rods could be put across the formwork with unions in between, so that as the formwork rose it would be possible to make adjustments on those unions and pull the silos back to the designed shape.

Mr Snow commented on the value of loud-speakers, which had been very useful for giving orders to the men working on silos. In bad weather or when working at night, it was often not possible to get a level on the silo when jacking up, and it might then be as much as 1 foot out—he thought Mr Broughton would confirm that. It would be necessary to correct that during the day, and with the aid of loud-speakers the situation could be explained to the men.

When building a silo 80–90 feet high, the walls of which were of the order of 5 to 6 inches thick, the roof had to be constructed, and unless the scheme had been prepared beforehand it would have been extremely difficult and dangerous for the men to remove the formwork for the bins and to construct shuttering for the roof without going to the bottom of the bins. Experience had shown that, by putting in two steel joists with an extensible end (so that it was possible to leave those two joists in position and extend them each side to overlap the wall) the existing formwork could be used to do the concreting for the roof, leaving a hole in the centre of each bin to get at the formwork to remove it. On completion of the concreting, an instrument constructed in the form of an umbrella was dropped down through the holes of the bins and then opened out inside the silo, allowing the formwork to be supported, dismantled, and then passed up through the previously mentioned hole in the centre of the bins. The alternative method—and a poor one—was to leave a large hole in the bottom of the hopper and drop the whole of the shuttering, leaving the hopper bottom to be constructed at a later period.

Mr Snow had first tried out the idea of a pictorial representation in the time schedule (*Fig. 22*) on a block of the Guinness Brewery silos. That added interest to the time schedule, particularly for a client who liked his facts presented pictorially.

Fig. 23 showed the Victoria Dock silos, where a world's record had been created for speed of erection; the date of that picture was 19 September, 1933. *Fig. 24* showed the same silos 5 days later. The walls were 90 feet in height and were constructed in 6 days 18 hours.

Mr H. H. Broughton said that he would not confirm Mr Snow's remark that it was quite common to have decks 12 inches out of level. He had never before heard of decks being 12 inches out of level.

Nowhere in the Paper did the Author say why he preferred to use hexagonal or other queer-shaped bins in preference to the circular form. Under the action of internal pressure, any bin, no matter what its shape,

Fig. 23

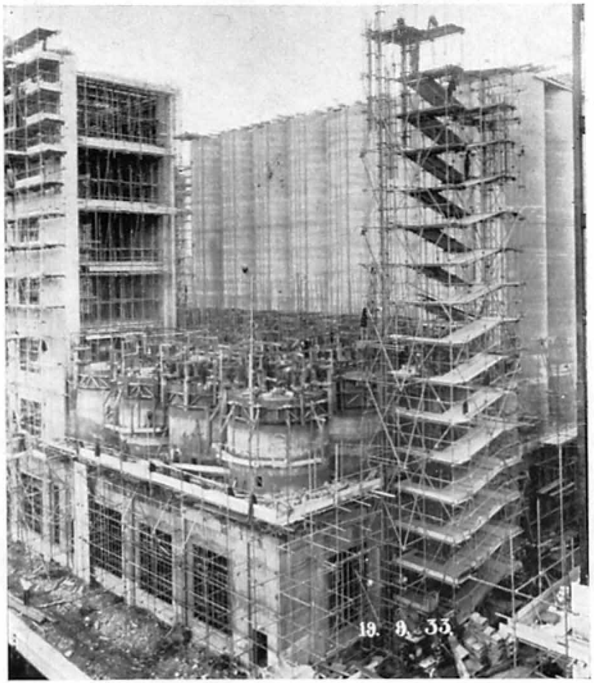
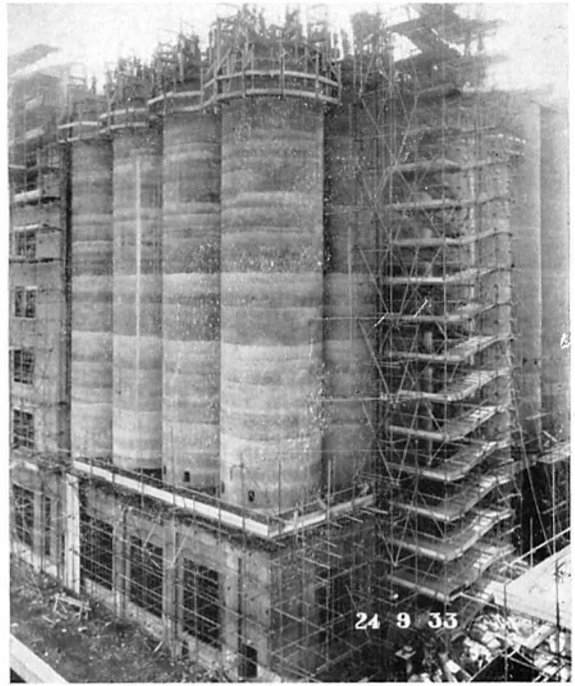
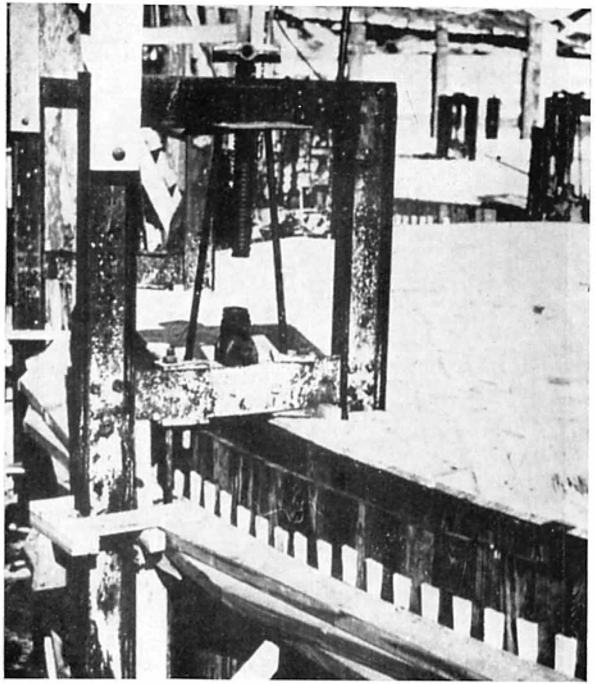


Fig. 24



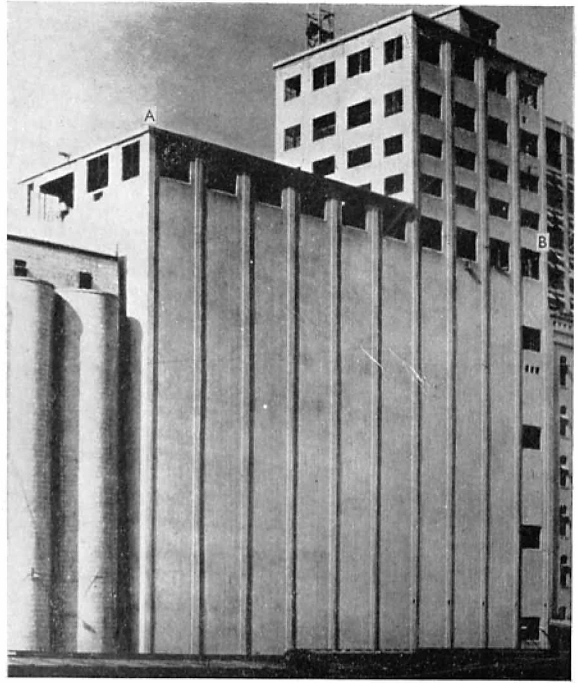
Victoria Dock Silos

Fig. 25



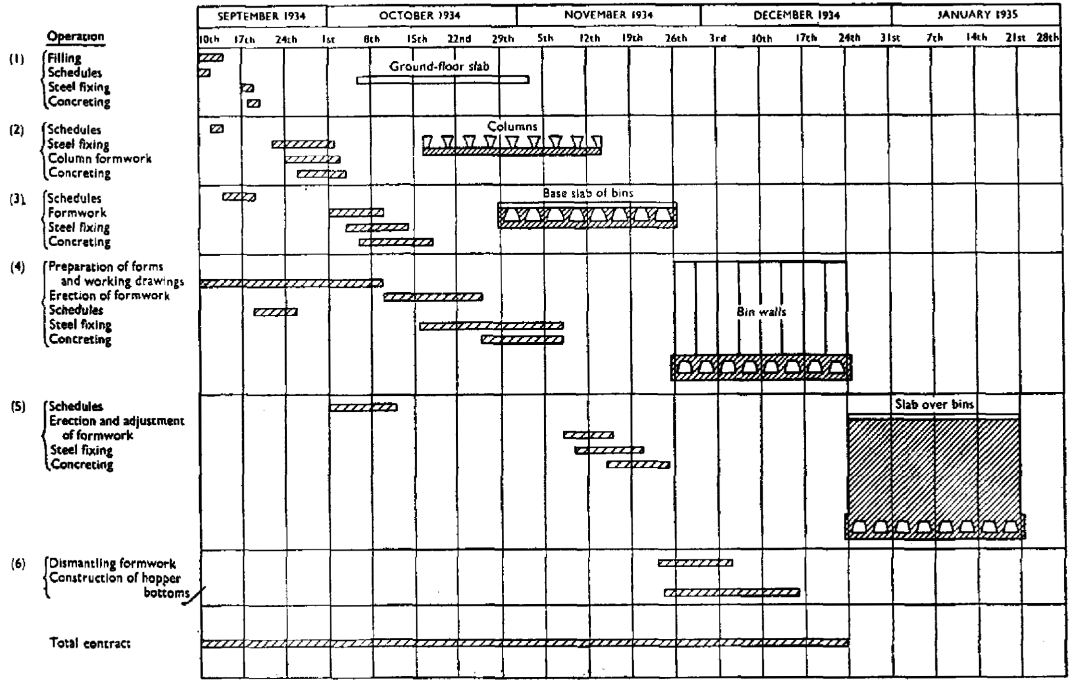
Modern Type of Yoke

Fig. 26



Silo of 17,000 Tons Capacity

Fig. 22



Pictorial Representation of Time Schedule

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tended to become circular, which was therefore the logical form. If *Fig. 7* were examined, it would be seen that there were bins of two different sizes. The main circular bin had a volume of about 500 tons, whilst the interspace bin had a volume of about 100 tons. By constructing walls tangential and on the outside, an end bin or quarter bin with a capacity of about 50 tons could be obtained. If, therefore, a small parcel of grain or mineral had to be stored, it could be put either in the end bin or in the interspace; that was the great advantage of circular bins over bins of other forms. If the bins were all of one size, "dead storage" was created, which presented great difficulty in the economical handling of material.

Reference was made in the Paper, and also in recently-published articles, to walls of fantastic thicknesses—4–4½ inches. Mr Broughton regarded 6 inches as the minimum thickness under any conditions for moving formwork; 7 inches should be used where possible, and perhaps 8 inches for larger bins.

Reference was also made in the Paper to the spalling of the concrete due to the internal corrosion of reinforcing steel. That was not reinforced concrete, nor was it good engineering.

The jack-rod spacing given in the Paper was 4–6 feet. He had frequently used 12–13 feet. It depended entirely on the arrangement, but it would not be advisable to regard 6 feet as the maximum spacing of the jack rods. The weight of jack-rod steel depended on the wall thickness and rod spacing, and varied between 10–18 lb. per cubic yard of concrete; 15 lb. was a good average.

He was sure that the Author would be one of the first to welcome criticism of the arrangement shown in *Figs 16*. *Figs 16* showed the arrangement of the yoke and jack, and the hanging scaffold, together with the method of supporting the walings from the yoke. That diagram represented the arrangement which Mr Broughton had used in about 1924, and which had been abandoned in about 1929. It worked, but not so well as the modern arrangement. Instead of the timber yokes, which weighed 297 lb. each, indestructible pressed-steel frames weighing 137 lb. were now used. It had been found that the jaw clutch worked quite well so long as the jack rod remained 1 inch in diameter, but no commercially-rolled rod could be relied on for constancy of diameter; if the diameter got small the clutch went the wrong way and locked on the rod, so that the clutch had to be dismantled. The modern clutch, therefore, took the form of a sleeve over the jack rod and was connected to the jack rod, and in the top there was a self-aligning ball and thrust bearing. The existing jack screw was used, but sleeves were now used instead of jaw clutches. That arrangement had reduced the cost of jacking.

The hanging scaffold should not be supported by or hung from the yoke, because it was necessary to retain the scaffold in position against the side of the building when the yokes had been removed, and that was not possible if the scaffold were attached to the yoke. The hanger was supported, therefore, directly from the walings. With regard to the support of the walings, four angles were shown in *Figs 16*. The objection to that was that it involved a rigid arrangement. The walings were secured by bolts or screws to the angles, and it was almost a physical impossibility to make any adjustment to the forms as work proceeded.

Mr Snow had referred to walls varying in thickness. Walls did not vary in thickness when the man concerned knew his job, because he corrected the forms as work proceeded. That was done by hanging walings straight to the top of the yoke, so that the tension went direct to the nut.

Mr Broughton was not certain, from reading the Paper, whether the Author believed in having architectural features or not. Ruskin had remarked that he would rather have been born blind than live to see some of them.

Fig. 25 (facing p. 27) showed the type of yoke which was now used. It had pressed steel legs. The clutch was shown clearly, and the jack screw. The wedges going completely round the form would be noted. Concreting had not yet commenced; something had happened, and the "draw" of the staves had had to be corrected by means of those wedges.

Without pilasters, the building shown in *Fig. 26* would look like a packing case. That building had to be in close contact with an existing building, and had been constructed using the wall of the existing building as the outside shuttering until reaching the level AB, where the higher part began. At that point a cut-off had taken place. Half the forms had been left behind, a new side form had been introduced, and concreting had then continued. That was a silo of 17,000 tons capacity; the bins were 109 feet deep and there was 30·4 cubic yards of concrete per foot of height—a total of 3,300 cubic yards. The tall building on the right was 172 feet high. The contact surface of the forms for the concrete was 10,400 square feet; the wall perimeter, therefore, was 2,600 feet. So far as labour costs were concerned, it was a pre-war job. For the forms, fabricating, erecting, maintaining, and dismantling, the whole of the labour costs had been 23·4*d.* per square foot of form. If 23·4 uses could be got out of the timber, it would be seen that the form cost for labour had been only 1*d.* per square foot. The figures which he gave were certified costs on which payments had been made.

The jacking costs for the lower part of the building had been 4·4*d.* per jack-rod foot. On reaching the higher part the work had become more difficult; it was a four-storey building, and the jacking cost had been 6·85*d.* per foot. The steel hoisting and placing had cost 39*s.* 10*d.*—about £2 per ton. The concrete had come on the site ready mixed. The hoisting and placing had cost 2*s.* 6½*d.* per cubic yard. The average progress had been at the rate of 11 feet per day, and the bins had been constructed in 10 days, whilst everything shown in the picture had been completed in about 3 weeks.

The subject of moving formwork was of sufficient importance to justify

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more consideration than had been given to it in the past. The equipment might be rather costly, but to those who were interested in construction, he suggested that the contractors should establish a pool among themselves. There might be a pool of, say, six-hundred jacks and other fittings necessary, and those who got contracts would draw on the pool, instead of having so much dead material in store year after year.

Mr G. P. Manning's first comment related to Airy's formula. If careful regard were given to the premises on which Airy based his results, it would be seen that there was a serious discrepancy, and it was surprising to find that anyone still used Airy's results.

With regard to sliding shutter work, the method described in the Paper was not the only one. For example, in one contract the contractor had a lot of old steel scaffold tubes and a large number of chain blocks, and had built the scaffold tubes into the walls as he went up, hanging the chain blocks from them and hoisting the shutters up continuously by that means. The Author had said that the formwork was constructed for both sides of the walls. That was not necessarily the case with moving shutter work, and the inside shutters could be slid and the outside ones brought up hand over hand. It was possible to slide a single-sided shutter.

The Author had suggested 4–6 feet for the spacing of the jack rods. In Mr Manning's view, a normal spacing on a straight-forward job would be about 7 feet, in which case each jack rod supported 56 square feet of shutters, in addition to a certain amount of decking. It was stated in the Paper that the shape of the silo should be designed to suit the formwork. That was so, but it was also necessary to arrange the steel, if sliding shuttering were to be used, so that it could be easily passed underneath the yokes. That was one drawback to the hexagonal shape, where the bar came up the side and turned at an angle. So far as the rate of sliding was concerned, the figures given in the Paper appeared to be on the low side. A fairly low average for a big job was 9 feet in 24 hours. The fastest slide of which he had any personal knowledge was 12½ inches in 1 hour and 16 feet in 24 hours. Under really good conditions it should be possible to maintain a rate of 1 foot per hour. The largest figure of which he knew was 72 cubic yards of concrete per foot of height, but there should be no difficulty in sliding jobs two or three times that capacity. The highest slide of which he knew was 140 feet, but there should be no difficulty in reaching 200 feet. He was not thinking of chimney work but of silo work as such. The thickest wall was 18 inches, and the thinnest silo wall 5 inches. The Americans did not favour sliding anything less than 7 inches ; in Britain one should certainly not slide anything less than 6 inches. Mr Snow had already raised the question of how thick a 6-inch wall was. Those who had seen sliding work could perhaps give a guess.

Mr Snow had also asked whether anybody had tried using steel shutters on sliding work. Mr Manning said that it had been done, but the application had not been of sufficient interest to give details of it.

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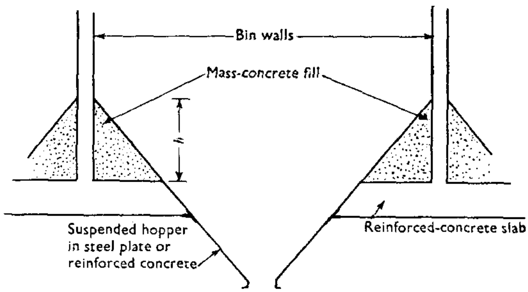
On the question of the design of silo bottoms, all silo bottoms were really the same type of design, as shown in *Fig. 27*, the shaded space being filled with mass concrete. The only variation was in the height, h. In a very small silo it paid to drop the slab so that the small hopper disappeared, but in a very large one it might pay to lift it so that the filling disappeared and it was practically all hopper. For the normal bin of 12–14 square feet it usually paid to put the slab about half way down.

It was stated in the Paper that the circular shape was more costly to construct than the hexagonal. That statement was only partly true, over a restricted range of sizes. In Britain the size of each individual bin in a battery of silos was fixed by the miller and by milling considerations. The miller wanted to handle his wheat in batches of 100, 200, or 300 tons, and

Fig. 27



so the engineer made the bins of the size required. In countries such as Canada, however, where enormous quantities of grain were merely stored until a ship arrived to take the grain away, the circular necked-out shape was undoubtedly the cheapest. The American and Canadian silo installations were all very large circular bins.

Mr I. Hey said that he had found a reluctance, particularly in Britain, to apply the sliding-form method to jobs equivalent to the Author's 3,000-ton bunker. The case was clearly made out for sliding forms for large grain-storage silos as used in North and South America. The Author had stated that the hexagon was the best shape if a number of compartments were required to form a honeycomb in plan, but admitted that for diameters larger than about 18 feet the circular bin was preferable, where the inter-space silos could be used. Why should not the inter-space be used in all cases ? Strangely enough, it was in Britain that engineers questioned the desirability or advisability of using the inter-space in a run of circular silos. In grain-storage silos where the loads ran up to 1,000 tons in big bins, there was, as Mr Broughton said, 20 per cent. of the load in the inter-space bins, and half that in the end bins. That was the universal practice ;

it was only in Britain—or with materials other than grain—that the inter-space was not being used, and then it was said that square or hexagonal bins were more economic than round bins. It was a matter of simple arithmetic.

He was pleased that Mr Manning had called attention to the type of hopper construction shown in *Fig. 27,* even though it meant building columns from the main slab and starting the sliding shuttering higher up, rather than building the columns and going right through. It was not possible to go ahead and complete the plan, because the contractor came back to build his hoppers and was a long time on those hoppers. With the slab formation that difficulty was avoided. Mr Hey thought that 7 metres was an economical size for circular bins of up to 30 metres in height. In the design, the factors relating to the progress of the job had to be taken into consideration. The basis of the advantage of sliding formwork was that by a fair amount of preparation and organization time was saved on construction. The steel mouth-pieces were easily fitted, but should not be fitted to templated bolts.

In *Figs 3* a type of construction of hopper bottoms for sticky materials was shown. It was known from experience that the best answer to the problem of handling sticky materials was to have two vertical sides. With two vertical sides he would not say that arching would not occur, but there would be no arching off a vertical side ; vertical sides would guarantee the best natural flow. That gave rise to a problem in the slope, but it was the most straight-forward answer and was far better than hanging the hopper on big bins from the direction of the top of the column. He had seen building formwork done in record time, 12 feet a day, and then it had been necessary to wait many months before the floor was free to start placing the machinery.

It was stated in the Paper that the design had to be correlated with the machinery and equipment. Mr Hey looked on storage as compensation between two systems of transport, from rail to ship or ship back to rail, or as compensation between sections of a process, but always in the sense of compensation. The Canadian and American grain silos were compensation as between producer and user and those forms of transport. The second factor was that, even when use was made of the best methods of constructing silos or bunkers, they were still very expensive ; therefore the mechanical handling or machinery process should be the first consideration, because storage was really a secondary function ; it was the machinery and plant and process which determined the earning capacity. Simplicity of design for the use of sliding forms would give a good line and contrast and a good-looking job.

So far as the thickness of the walls was concerned, he advocated a thickness of 6 inches to give protection against the weather, but they had to be good walls. He did not like to go down lower than 5 inches, because it was not possible to ensure a proper cover on the steel ; but it could be

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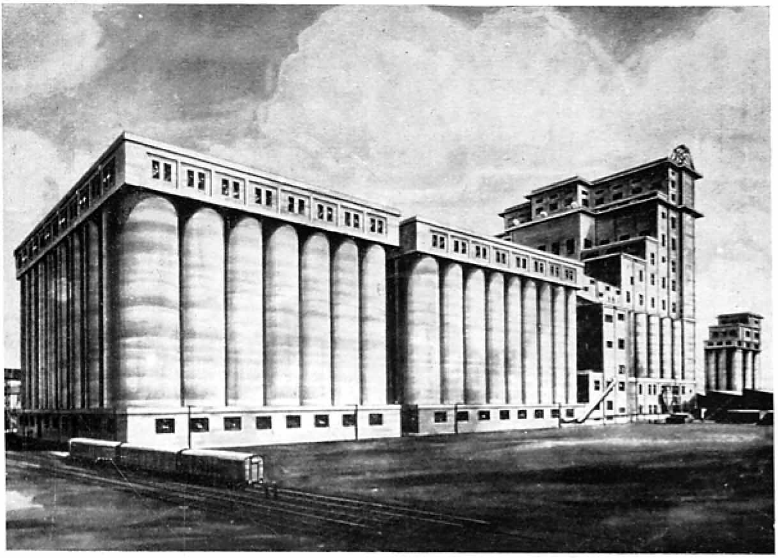
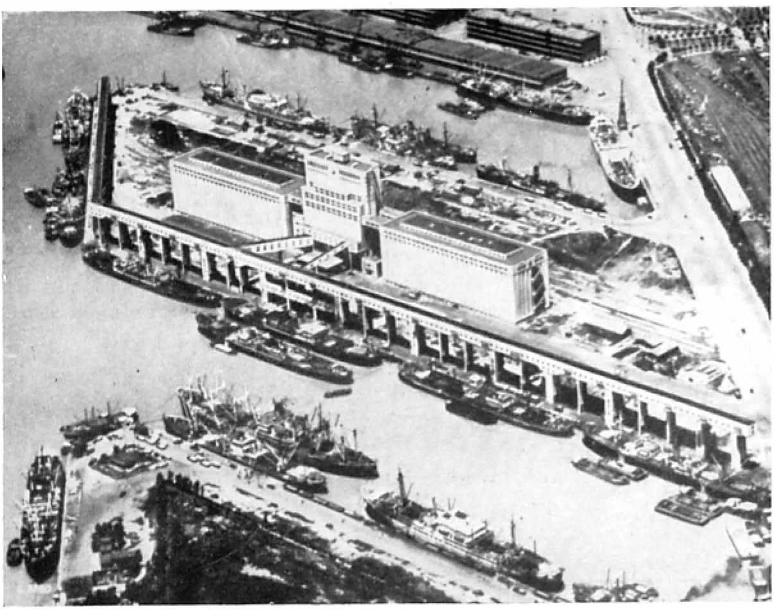
Fig. 28



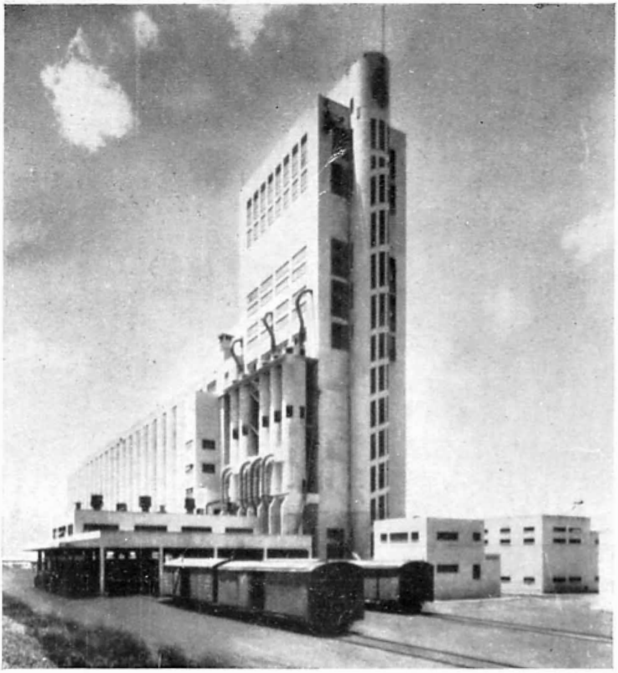
Grain Elevator at Ingeniero White, 140,000 tons Capacity—
The Argentine

Fig. 29



The 150,000-ton Elevator at Puerto Nuevo, Buenos Aires

Fig. 30



The 54,000-ton Elevator at Villa Constitucion, the Argentine

Fig. 31

Another View of the Elevator Shown in *Fig. 30*

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done, and there were numerous jobs where it had been done and which were very satisfactory. How Mr Snow came to have so great a variation in the thickness of the wall he did not know; that had not been his own experience. Perhaps the formwork had been weak somewhere in that design.

Sliding formwork applied to the construction of big grain silos was well illustrated by the example shown in *Fig. 28,* which was in the Argentine, and had a storage capacity of 140,000 tons, was 92 feet high, with bins of 18 feet in diameter. It had been done in three lifts, and each of those two blocks had taken 8 days to build. The receiving house on the right was part of the big building. There were bins in between the main floors, which had been stopped for several hours because they introduced bin bottoms for dividing the bins, bottoms for elevator legs which did not run right through, and there were small walls for the elevators. The stoppages had been quite frequent, but the 60 feet of those bins had been carried out from Monday afternoon to Friday morning, working with squads of men of twenty-two different nationalities. Since 1932, when it had been built, it had handled 1,000,000 tons of grain a year, and in October 1947 it received and shipped 200,000 tons of grain in the calendar month, which he thought was a record.

Fig. 29 showed a 150,000-ton silo in Buenos Aires; it was possible to feed five ships simultaneously from that plant. *Fig. 30* was an example of moving formwork for a 60,000-ton silo, and *Fig. 31* was another view of the same elevator.

Mr F. G. Etches, dealing with the aesthetics of design, observed that it was inferred in the Paper that engineers did not consider sufficiently the appearance of their structures. Whereas that might have been true 20 years ago, he did not think that it applied to-day. It was certainly true that both bunkers and silos needed special thought and care in planning, because large surfaces, unbroken by window or door openings, and usually without an interesting surface texture, presented certain problems. That was especially true of silos which were situated near a dock or on the banks of a waterway, which tended to exaggerate their height and to make them appear out of proportion to their surroundings.

One solution was to attempt to create a simple self-contained and balanced structure which did not dominate its neighbours. Mr Etches described a medium-sized silo in which small projecting piers, which were made visible by the shadows they cast, were used to give form to the building. In that building there was no wasted space, and 90 per cent. of the area, and therefore the volume, was available for useful storage. Another silo, of the same general arrangement and overall size, had eight octagonal bins. The shadows on the elevation gave a broken and rather restless surface, which he thought was also shown by *Figs 17–19* in the Paper—the latter were hexagonal bins, but the same point was illustrated. Rather less than 80 per cent. was available for storage, and that included

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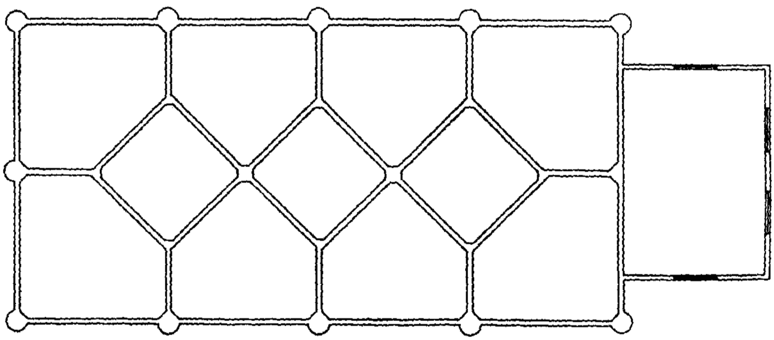
the small square bins which, for grain storage, were often an advantage. They stored about one-quarter of the quantity held by the large bins, and gave more flexibility for different quantities and qualities of binned material.

A circular bin gave probably the most interesting surface, as revealed by shadows. One such lay-out had 70 per cent. of useful storage area, although again small bins were used. Another was a variation of the square bin, but was improved by the addition of semi-circular piers. If some justification had to be made for those piers, apart from appearance, they could enclose rainwater down-pipes. Almost the whole area was available for storage; in addition, there was the advantage of small bins,

Fig. 32

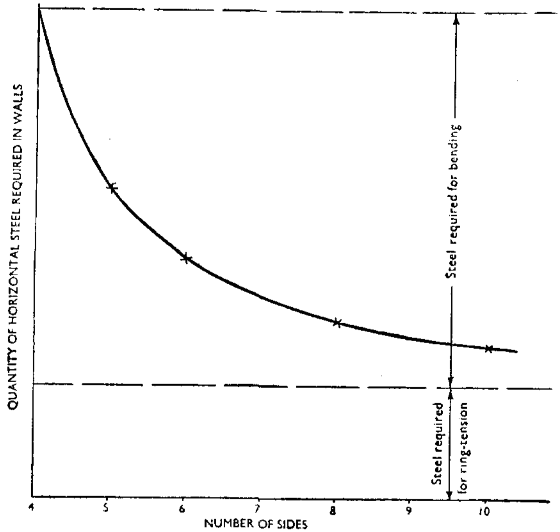


PLAN OF BIN WALLS

and the plan cut down the large span of most of the walls, except the outside walls, as shown in *Fig. 32*.

With regard to the quantity of steel necessary in the bin walls, which was influenced by the bin shape, the economics of any particular lay-out of bins had to be investigated for each case, but the quantity of steel ıecessary lent itself to some general conclusions. *Fig. 33* showed an dealised curve for a bin of given size, with the quantity of steel plotted gainst the number of bin sides. The lower part of the curve showed the teel required for ring tension, and was constant for all regular shapes of in. Mr Broughton had made the point that all bins tended to become rcular. The upper part of the curve from the dotted line upwards, to e same scale, showed the steel required to resist bending stresses. That uld be maximum for a square bin, and was reduced inversely as square of the bin size; it was equal to zero for a circular bin. The n of the two ordinates (the total vertical ordinate) would be a measure he total quantity of steel needed for any given set of conditions. The l required in the hexagonal bin was considerably less than that for the are bin of the same overall size; in other words, the curve was steep to the left; but the saving was likely to be very much less for a greater number of sides.

Fig. 33



COMPARISON OF HORIZONTAL WALL STEEL REQUIRED FOR A GIVEN SIZE OF BIN FOR VARIOUS GEOMETRICAL FORMS

Mr R. H. Squire questioned the validity of formula (3) given in the Paper. If the slope of the bottom were as shown, and a small unit area were considered (see *Fig. 34*), the vertical force (P_v) acting on that area would be $wh \cos \theta$. The horizontal force (P_H) would be equal to $wh \cdot \frac{1 - \sin \phi}{1 + \sin \phi} \cdot \sin \theta$, or substituting p for wh in the first case, and p_1 for $wh \cdot \frac{1 - \sin \phi}{1 + \sin \phi}$ in the second case, $P_v = p \cos \theta$ and $P_H = p_1 \sin \theta$. Those were forces and not pressures, and so the dotted line represented the resultant (P), P_N being the normal and P_T the tangential component. In the Paper there was no mention of P_T, but it was not possible to ignore it.

By inspection of *Fig. 34*,

$$P_T = P_v \sin \theta - P_H \cos \theta$$
$$P_N = P_v \cos \theta + P_H \sin \theta$$

substituting $p_1 \sin \theta$ and $p \cos \theta$ in those equations for P_H and P_v,

$$P_T = (p - p_1) \sin \theta \cos \theta \text{; and}$$
$$P_N = p \cos^2 \theta + p \sin^2 \theta.$$

The latter was the expression given in the Paper, and the former was the expression for the tangential component.

He emphasized the fact that the tangential force had to be taken up somewhere, and the only point where it could be taken up was by friction on the bottom, so that the angle α could not exceed ϕ'—that being the friction angle between the material and the bottom. Therefore formula (3) was only valid for obtaining the normal pressure when $\frac{P_T}{P_N} \ngtr \tan\phi'$. If that were greater than $\tan\phi'$ it would be necessary to make an adjustment somewhere. Clearly it was not possible to adjust P_v, the dead weight of the material, which might or might not be reduced by friction on the upper

Fig. 34

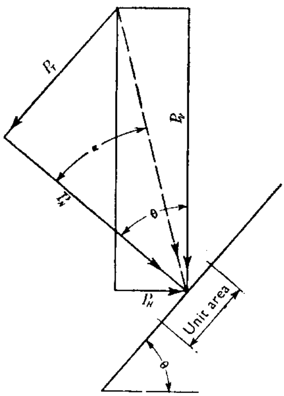
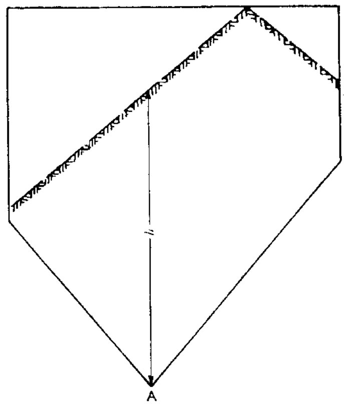


Fig. 35



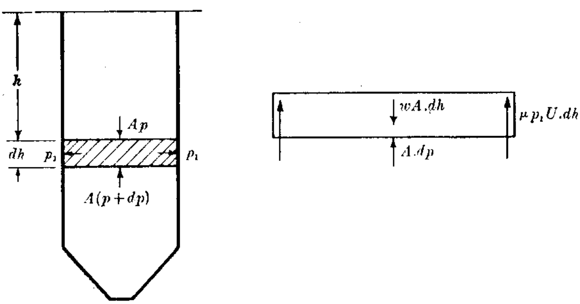
parts of the walls, according to whether or not a deep bin or deep silo formula was being used, but if, having taken Rankine's or some other value for the horizontal pressure and the friction on the bottom into consideration, the material still wanted to slide down, it would be necessary to increase the lateral pressure; that could make a considerable difference. A solution could be obtained graphically by making the angle α equal to ϕ' and getting a revised value for P_N, or by equating $\frac{P_T}{P_N}$ to $\tan\phi'$, and obtaining mathematically the value of p_1.

With regard to the effect of unequal, unsymmetrical bins or unsymmetrical loading, using the Author's formula, the pressure on the bottom would be dependent on the depth h (see *Fig. 35*), so that at point A there would be the same normal pressure on each side; the pressure on the vertical plane through A taken one way, however, would be different from the pressure the other way, one being a positive surcharge and the other a negative one, and also the sliding effect was almost always present.

If the friction angle was going to hold the material against sliding, there would be a very sluggish discharge, if there were any discharge at all. Reference was made in the Paper to the use of glass or similar lining for the bottom to improve the discharge. In that case, he thought that the normal pressure which would be taken on the bottom of the bin would not be the same as if it were a concrete surface.

*** **Mr Adolf Fruchtlander** thought that the remarks in the Paper regarding the pressure calculations and two standard formulae of Janssen and Airy gave the impression that those formulae were more of an empirical than a theoretical nature; that was not so. The basic constants had been determined, as in all theories of structures, by experiment. Janssen's formula had been developed about 50 years ago on a purely theoretical basis; it had later been checked on models and buildings by

Figs 36



engineers, such as Luft, and found to be in agreement with the results of the experiments. Since then the formula has been accepted as standard for that branch of engineering.

Mr Fruchtlander then described briefly the theory of the formula in question. Using the same notation as that given in the Paper, but replacing the friction coefficient tan ϕ' by μ, the formula became:

$$p_1 = \frac{wA}{\mu U}\left(1 - \frac{1}{N}\right)$$

In *Figs 36*,

$A.dp$ denoted the increment of vertical pressure,

$wA.dh$,, ,, ,, weight of material,

$\mu p_1 U.dh$,, ,, ,, side-wall pressure due to friction between material and wall.

The equilibrium equation for those forces acting on an element at a depth h was:

$$A.dp = wA.dh - \mu p_1 U.dh. \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

*** This contribution was submitted in writing.—SEC. I.C.E.

Therefore

$$\frac{dp}{dh} = w - \mu p_1 \frac{U}{A} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Putting $\frac{p_1}{p} = k$ (constant), or $dp_1 = k.dp$, equation (2) became :

$$\frac{dp_1}{dh} = kw - \mu k \frac{U}{A} p_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The solution of that equation was :

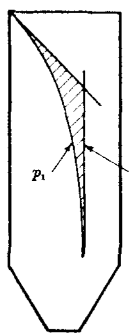
$$p_1 = \frac{Aw}{U\mu}\left(1 - e^{-\mu khU/A}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

which could easily be verified by differentiating equation (4) with respect to h. Equation (4) could also be written :

$$p_1 = \frac{Aw}{U\mu}\left(1 - \frac{1}{N}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where $N = e^{-\mu khU/A}$, and $\log N = \frac{U}{A} \cdot \frac{\mu kh}{2{\cdot}303}$.

Fig. 37



In practice, for a depth h more than 10–15 feet, N was a large number and the term $\left(1 - \frac{1}{N}\right)$ approached unity.

Equations (4) and (5) therefore reduced to :

$$\text{Maximum } p_1 = \frac{Aw}{U\mu} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

If the curve shown in *Fig. 37* represented the pressure values according to equations (4) and (5), the vertical line the asymptote to the curve for $h = \infty$ (according to equation (6)), and the sloping straight line the pressures according to Rankine's formula $p_1 = wh \tan^2 (45 - \frac{1}{2}\phi)$, *it would, in* general, be practicable to use the two straight lines for the design of the walls; that greatly simplified calculations, gave a good margin of safety, and scarcely affected the economy of the design.

The Author, in reply, said that he very much regretted his inability, due to illness, to introduce the Paper personally, and expressed his sincere appreciation to Mr Leopold Brook for undertaking the task and for showing the lantern slides.

The Author was glad that the Chairman had called attention to a failure of the foundations of a silo constructed in Algiers. That type of failure was usually due to the lack of consideration of the pressures on the strata below the surface. In the case of isolated foundations at a fairly generous spacing, that was not of great importance, but in the case of silo or bunker foundations where a high-intensity pressure occurred over a comparatively large area, the intensity of pressure on any weak strata below the surface could be ten or twenty times higher than it would be under any normal foundation condition.

The thickness of a silo wall was arrived at by the ordinary methods of design against flexure combined with direct tension, in the case of straight walls, and by limiting the overall tensile stress (ignoring reinforcement) to 200 lb. per square inch. It was essential to provide sufficient reinforcement to take the whole of the tensile stresses. If the silo walls were designed on that principle, no difficulty would arise in making them weather-tight.

With regard to formula (3), it would be noticed in an earlier paragraph that that formula was intended to refer only to shallow silos and would not be applicable to a deep silo.

Mr Snow's remarks regarding timber construction were quite true and well recognized.

Steel formwork had been used for continuously moving forms, but they had the disadvantage that, in general, they weighed and cost more than wooden forms. They had the advantage of not being affected by changing moisture and climatic conditions.

There was, as Mr Snow had suggested, a risk of distortion taking place in wooden forms, but that was usually taken care of by constructing a rigid framework at decking-level between the inner forms of the outer walls. Provided that that framework was held rigid and kept vertical, the outer forms could be lined up by adjustment of the yoke tie-bolts. Triangulated tie-bolts were very useful in overcoming any distortion difficulties.

A loud-speaker system on a continuously moving job was a great advantage, but the Author had not experienced the necessity of correcting the levels of the forms by as much as 1 foot. That would, in most cases, be a very difficult thing to do, and the forms should not be allowed to get so far out of level.

It was agreed that the removal of the formwork from a silo roof was a difficult and dangerous job. In many cases, the use of steel joists as the main members was a great advantage in that direction. The suggestion of the umbrella type of form described was interesting, as was also the pictorial representation of the progress schedule.

Hexagonal or other queer-shaped bins were used principally to simplify the distributing and collecting conveyor systems. As pointed out by Mr Broughton, that was not so important when dealing with free-flowing materials, such as grain, where steel spouts could be used to direct the material on to the conveyors. In the case of silos which were circular in plan, inter-space bins were useful for storing experimental consignments of the material. Where tapered walls had been used, as in the case of square silos, they had been frequently reduced from, say, 8–10 inches at the bottom to $4\frac{1}{2}$ inches at the top. For walls of uniform thickness, 5 inches was the absolute minimum that could be used. Any increase on that made placing of the concrete easier and was worth the small increased cost of materials.

A spacing of 12–13 feet for yokes, as suggested by Mr Broughton, seemed to be rather wide. The Author had found that anything more than 8 feet could cause difficulties.

Mr Broughton's illustration of a steel yoke (*Fig. 25*) was interesting, but it did not matter a great deal what material was used for the yokes, provided that they were sufficiently strong. Any design which reduced the weight of the equipment gave a definite advantage. The Author had not experienced any difficulty from the inequality in the diameter of commercially-rolled jack bars. Cantilevers, supported from the tops of the walls, were used to overcome the difficulty of keeping the hanging scaffold in position after the yokes had been dismantled.

One of the features of continuously moving forms was that the cost of the work varied considerably from job to job. There were so many factors which influenced the cost, such as the weather, availability of labour, and site conditions.

The cost of equipment was high, especially at present, and that made it difficult to introduce alterations to equipment which might otherwise be an advantage. Some scheme of pooling equipment would be a great advantage.

In reply to Mr Manning, the diagram shown in *Figs 14* was intended to give a comparison between results obtained in applying different formulae to one or two simple problems. It would be noticed that, in the case investigated, Airy's formula did give higher pressure-values for deep bins than other formulae, and that result was typical.

The method of hoisting forms on chain blocks described was quite common and was used almost exclusively in America for the construction of chimneys.

The speed at which forms could be lifted was governed by the hardening of the cement. It was essential that the concrete, when leaving the bottom of the forms, should have hardened enough to stand up without support.

The rate of hardening of cement varied considerably under varying atmospheric conditions, and the rates of progress given by the Author were average rates based on average conditions. If higher average rates were aimed at, a good deal of luck was required in striking ideal conditions, and much care was needed in choosing and maintaining the consistency of the concrete.

The Author agreed entirely with Mr Hey that inter-space bins should be used wherever possible, and it was usually only when dealing with materials other than grain that the hexagonal or other shape, as an alternative to the circular, was an advantage. The examples of silos described and illustrated by Mr Hey were extremely interesting and formed a valuable contribution to the discussion.

The Author agreed with Mr Etches that silos and bunkers generally were very difficult structures to treat aesthetically; and that, in order to overcome the problem, engineers were induced to introduce ornamentation which was entirely out of place.

The area occupied by the plan of a set of silos, although important, seldom had a predominating influence on the design, because in most cases site areas were generous.

Mr Etches's curve (*Fig. 33*), indicating the quantity of steel required in walls for varying shapes of bins, emphasized the point that the shape did influence the cost so far as the steel quantities were concerned.

Mr Squires's analysis of the pressures on the bunker slope were quite correct, but it would be noticed that, even when using his formula, the normal pressure on the slope, which was an important one, was not affected. When the outlet gate of the silo or bunker was opened and the material began to flow, the friction between material and the hopper slope broke down immediately, and consequently the slope of the bottom had to be greater than the friction angle, otherwise the material would not flow. The Author had pointed out earlier in the Paper that the value of mathematical formulae in the design of bunkers was very limited.

The explanation of varying pressures due to varying depths of material, as explained in *Fig. 35*, was interesting, but in most cases it was advisable to assume that a bunker was filled to the top, so that it would not be overstrained in an emergency.

Mr Fruchtlander had quite rightly pointed out that the Janssen and Airy formulae could be considered in some ways to be theoretical, but they were based on practical experiments and the derivation of the formula which he had given did add considerable value to the discussion.

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