

has been fixed the location of the anchor follows, the depth being obtained from a further curve.

The Author's firm, Messrs. W. T. Halcrow and Partners, were the Engineers for the work at Beira and acted jointly with Messrs. Coode, Wilson, Vaughan-Lee and Gwyther and Messrs. Wolfe Barry, Robert White and Partners as Engineers for the war work.

The Paper is accompanied by eleven sheets of drawings and one photograph, from which the folding Plates and the figures in the text have been prepared.

### Discussion.

The Author introduced the Paper with the aid of a series of lantern slides.

Mr. F. E. Wentworth-Shields said that the Paper described many novelties, and dealt with both the science and the art of engineering in a very delightful way. One note of warning, however, should be sounded. The suggestion had been made that cast-iron had a great advantage over steel on account of its high resistance to corrosion. He supposed that most engineers had been brought up to think like that, and indeed until a few years ago he himself had been of the opinion that cast-iron was a marvellous material for resisting corrosion in sea water, because of the very good appearance of castings which had been exposed to sea-water conditions. But many people had received a shock when the Committee on the Deterioration of Structures in Sea-Water (the "Sea Action Committee"), in its Eighteenth Report, published in 1940, stated that after careful examination of cast-iron plates which had been immersed for 15 years in sea water in various parts of the world, much more serious corrosion was found, measured in the form of weight lost per unit of exposed surface, than even with wrought iron or steel.

Cast-iron did not rust in the ordinary sense of the word. It formed a skin, of oxide mixed with graphite, which was very difficult not only to detach but even to detect. On p. 9 of the Report The Committee further stated that:—

"... the experiments indicate very clearly that superficial examination of the bars gives no indication of the extent of corrosion, which may penetrate to considerable depths, leaving nevertheless a hard compact surface coat which may easily be mistaken for original uncorroded metal."

Indeed it was only when a special method was adopted for removing that grey material by electrolytic action that it was discovered that quite

a considerable thickness of the surface material had no real strength at all. He did not suggest that cast-iron was not an excellent material for the work described in the Paper. He supposed that the most important part of the cylinders would be the screws, which, buried in the silt, probably suffered no corrosion whatever; but it was perhaps hardly right to say, as was suggested on p. 11, *ante*, that a hollow cast-iron pile was more resistant to corrosion than a solid steel pile.

The idea of double and treble screws on the cylinder was excellent. Fig. 6, Plate 1, which recorded the settlement under load, indicated that that settlement was not mere consolidation of the clay; and if the load had continued very much longer the material would possibly have broken down altogether. At the same time, the crane loads on such a jetty were not continuous, but intermittent, and no doubt the design was ample for the loads involved.

In order to admit of comparison with the soil conditions there and elsewhere, he hoped it would be possible for the Author to give the results of any tests which might have been made on the undisturbed samples of silt alluded to on p. 19, *ante*. A great deal was heard about classification of soils under their water-content and under their liquid and plastic limits and so on; but in order fairly to compare soils of one place with soils of another what was wanted was knowledge of the shear strength of the soil under no load and under some load. If that were known, it could be compared fairly with the soil in a different place. If such information could be given about the Beira soils, that would afford an opportunity of deciding whether a similar design would be useful in another place where the strength of the soils happened to be known.

He wished to congratulate the Author on the very neat diagrams of Figs. 12, Plate 2, which showed at a glance the dimensions which sheet-piling should have if it were driven into and backed up with sand. He felt sure that the Ministry of Works and Planning would want to steal that "peal of thunder" for their new code of practice on retaining walls. Indeed, the Minister might desire the Author to prepare similar diagrams for typical clays. Such diagrams simplified matters to such an extent that many people might be inclined to say that the design was made so easy that it might be left to a junior draughtsman. Personally he would say so much the better, because then the time of the chief engineer could be devoted to solving the various difficult problems which were sure to arise in a work like that described by the Author.

Lieut.-Colonel C. W. Knight, R.E., observed that most engineers had their pet subjects, and screw cylinders happened to be one of his. Moreover, it had been his privilege to be, for the best part of 2 years, the C.R.E. in charge of the construction of the deep-water wharf described by the Author on pp. 15 *et seq.*, and he had therefore been in close touch with all the problems involved, right from the inception of the work. Therefore, in view of his knowledge of the circumstances which led to the adop-

tion of the particular design, it would be appreciated that his remarks would be of a confirmatory nature, rather than critical or interrogatory.

The Author had rightly indicated that prior to the construction of the wharf, screw cylinders had been chiefly used for foundations by sinking and founding them on a hard stratum underlying a soft alluvial deposit, for which conditions they were very suitable. But the problem at the site of the wharf in question was different. There was no hard stratum below the soft material, and, as the Author had pointed out, the cylinders had to be founded in the alluvium and a method devised of distributing the load within the bearing capacity of the soil.

Normally that would have been done by increasing the size of the screw-blade rather than by adding one or two screws to the cylinder. That would have saved weight and consequently cost in cast-iron, and would have made erection easier. However, the deciding factor was time, not expense, and it was found that screws of 7 feet and 8 feet diameter could be obtained much more quickly than screws of 10 feet diameter—a size which, he thought, had not yet been manufactured, but which he would have no hesitation in using.

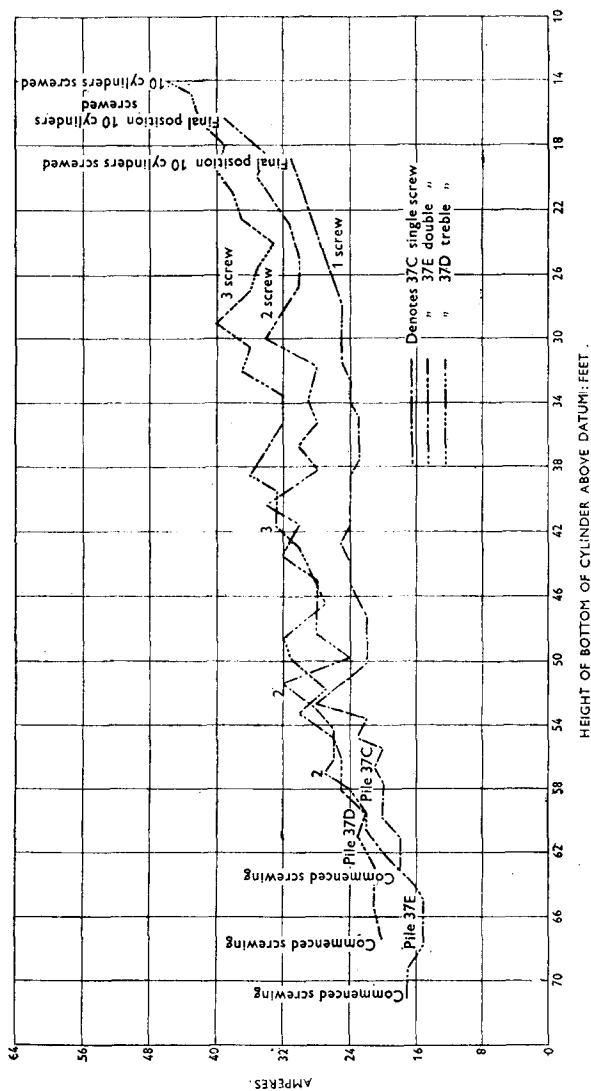
As a larger screw was out of the question, it was decided to explore the possibility of adding one, or even two, screws to the cylinder where necessary. Tests were made, the results of which were tabulated on p. 14, *ante*, and from them the general conclusion reached was that a double screw would take 50 per cent. more load than a single screw, and a triple screw twice the load of a single screw.

That established a very important relationship, but there was one point he wished to raise. At the site the soil was similar in texture throughout the whole length of the cylinder, so that the two or three screws, as the case might be, were all resting on soil of equal bearing-capacity value. But what would happen if they were not of the same value? That question had cropped up several years ago on a job on which he was engaged, where the screw was founded on hard material which did not quite come up to expectations, and which was found insufficient to take the full load. Consideration was then given to adding another screw to the cylinder, and considerable argument arose as to what would happen. The bottom screw was in soil capable of taking 5 tons per square foot, and the upper screw would have been in soil capable of taking  $1\frac{1}{2}$  ton per square foot. Would the bearing capacity of the combined screws be, say,  $6\frac{1}{2}$  tons per square foot? The matter was never tested out, as other methods were adopted in dealing with the problem. He wished to suggest to the Author that if such a test could be made, it would provide valuable information.

The Author had referred to the extra power required for turning the additional screws, and had stated that, as the soil was so soft, it was thought that the extra power would be within the capacity of the plant at the site. That was a perfectly correct forecast, and the extra power needed was very small. *Fig. 13* indicated the power required for each particular

cylinder. The lower graph represented power used for a single screw cylinder, the central graph that for a two-screw cylinder, and the upper graph that for a three-screw cylinder. For a real comparison, the diagram

Fig. 13.



should be studied after the third screw had entered the ground. The final values were 31, 39, and 46 amperes respectively.

Another point upon which he wished to comment was the improved performance of the cylinders after reconsolidation. It would be noted that the bearing capacity of the cylinders under load improved considerably after being left for 10 months. As a matter of fact, the cylinders tightened up very quickly, and that was a point that had to be watched in erection. An unfinished cylinder which was left for some reason for two or three days, or even overnight, could sometimes be very troublesome to start again. Before any unfinished cylinder was left, it should be unscrewed for one-quarter or one-half turn; no trouble should then occur in re-screwing.

The question of the adoption of a closed- or open-ended screw was also very important. The Author had stated that in soft ground it was possible to screw the cylinders with the end closed, but that in harder ground they were screwed with the end open. That was perfectly true. Resistance to screwing depended upon the degree of compressibility of the soil. If the material were soft and easily compressible, a closed screw might be used, but in clay, gravel, or sand, which were not easily compressible, an open-ended screw was advisable, so that the internal core could be removed by an air-lift during the process of screwing. That was equivalent to a carpenter boring a hole in a piece of hard wood before inserting the screw, and was the secret of getting the cylinder down.

He would sum it up by saying that if trouble were encountered owing to obstructions, hard layers, refusal to penetrate, etc., the engineer on the site would be very comforted to feel he had an open-ended screw at the bottom of the cylinder, as he could then tackle his problem from inside the cylinder.

If one was perfectly sure that the soil was easily compressible the closed screw made a neater job. An extra 7 square feet of bearing area was obtained, the extra buoyancy was a convenience in erection, and the cylinder could be completely filled with concrete in the dry if required; but one could never be certain of the compressibility, as borings taken through water were so frequently unreliable, and after many years' experience with screw cylinders in various soils, he did not hesitate to say that he would sacrifice such advantages in favour of having an open-ended screw.

At the site of the wharf there was doubt about the nature of the soil. As a matter of fact, it was much softer than was expected; hence the additional screws to obtain the necessary bearing area. But the advantages of the open screw in overcoming difficulties, and therefore in saving time, were fully realized, and arrangements were made for the closed ends of the screws to be detachable, so that if necessary they could be discarded altogether.

However, the screwing was found to be very easy—too easy, in fact—and the extra bearing area of the closed end was welcome.

Near the shore, however, a thin layer of clay and shingle was encoun-

tered, through which the cylinder with the closed point would not penetrate and had to be left. Open-ended cylinders were sunk adjacent to it, and by taking out the core with an air-lift the open-ended screw could be easily made to penetrate.

That only proved that, as stated above, if trouble were encountered it could usually be overcome with an open-ended screw.

The work described in the Paper was the first instance of 3-foot diameter cylinders being screwed in Great Britain by modern methods, though it was a very popular method of construction for deep foundations abroad.

He had no doubt that the Paper would attract a good deal of attention from British engineers, to whom it would open up further fields of study in the consideration of their deep foundation problems. By its contribution the Author had permanently enriched the engineering records of The Institution.

**Mr. F. M. G. Du-Plat-Taylor** observed that the Paper dealt with a subject rarely ventilated at The Institution.

He had few remarks to make, but those went rather to the root of the matter. He wondered whether, before the system described was adopted, consideration was given to a totally floating structure like the passenger landing stage in Liverpool.

He saw no difficulty in making such a structure to carry cranes and railway traffic or in bringing the railway traffic on and off the floating stage by means of articulated bridges.

The Liverpool landing stage—and, he thought, also the London one—carried fairly heavy passenger landing gangways, which travelled along the stages on rails. He did not suppose those were as heavy as cranes, but that was only a matter of degree.

One advantage would be speedy construction and another the possibility of removing the landing stage from one site to another, if required. That would mean dismantling the deck structure, conveying it to the new site for re-erection, and towing the pontoons to the new position. The whole thing could be re-assembled in a new place.

Though the idea seemed quite feasible to him, he had had no opportunity of working the matter out in detail.

A second suggestion was that much larger cylinders, of mild steel plate, might be used, so as to take advantage of their buoyancy. The power required for screwing the 3-foot cylinders was given as 5 horse-power per screw, so that the power required for screwing much larger cylinders would not be out of the way.

A 10-foot diameter cylinder sunk to 50 feet below high water would have a high-water buoyancy of 112 tons, less its own weight of  $7\frac{1}{2}$  tons, giving a net buoyancy of  $104\frac{1}{2}$  tons. Similarly a mild-steel cylinder 12 feet diameter would have a net buoyancy of 159 tons. Changes in level due to the rise and fall of the tide would be uniform throughout the structure and would be but slight, and it seemed to him that there would be considerable

advantage and economy in that arrangement in soils which were practically semi-liquid mud.

**Mr. J. S. Wilson** observed that although the Paper referred to the construction of wharves on soft alluvial material, the method appeared to be applicable to harder materials also. As far as he knew, the work described was the first in which twin and triple screws had been used. The Paper clearly demonstrated the increase in the supporting power of the additional screws, and for that reason he considered it of great value to all interested in the construction of wharves. The information given of the increase in supporting power was so valuable that he regretted it was not more complete and the graphs a little clearer. Regarding the latter point, the settlement of 1.6 inch stated on p. 16 did not agree with the graph in Fig. 6, Plate 1, which suggested 1.06 inch. Also in the detached part of Fig. 6 on the right, the fragment of curve at the bottom looked as if it should belined to agree with the first loading of the triple screw. In the loading graph at the top of the figure he could not follow the loading that corresponded with the settlement graph for the second loading of the triple screw.

The preliminary investigations by the photo-elastic method referred to on p. 18 having proved encouraging, he hoped the Author would publish his results. They would be particularly interesting to Mr. Wilson, as he had used a photo-elastic method with rubber for investigating stress-distribution.

The cast-iron cylinders used at Beira and at one of the wharves described were of interest to him as he had assisted in the inspection of them and in following progress in manufacture. The interesting feature was that each length of cylinder had to have accurately machined end flanges with holes drilled for sixteen turned bolts. To transmit the powerful torque the bolt-holes were required to be only  $\frac{1}{32}$ -inch larger than the bolts. The average foundry turning out heavy castings was not used to working to fine limits and as all the segments and screws had to be interchangeable, interesting problems relating to tolerances in the various dimensions had to be solved. The cumulative error in the spacing of the holes around the pitch circle together with that in the pitch diameter combined with the errors in the drilled holes after allowing for errors in the jigs, possible wear in the bushes and drills, all taken together had to come within the  $\frac{1}{32}$ -inch. The jigs had to be watched and bushes replaced when worn and the drilling was finally checked with special gauges, having projecting plugs to represent the bolts, which could be applied to the drilled flanges.

**Mr. Wilson** considered that the Author and his firm were to be congratulated on having introduced an important advance in the construction of wharves.

**Mr. L. F. Cooling** observed that the Paper contained some very valuable data. He wished to comment on the properties of alluvial deposits such as those found at the site of the deep-water wharf. As mentioned on p. 18, *ante*, it had not been possible to obtain samples of silt

for laboratory tests at the levels to which the screws were driven. The two samples of the silt were taken from just below bed-level. He gathered that those samples were procured by the Author in rather unorthodox fashion by slowly forcing into the soil a plan-case (5½-inch internal diameter) with its bottom end open, and a small hole in the cap at the top, the services of a diver being requisitioned for withdrawing the samples.

The samples were examined in the laboratory at the Building Research Station. One sample was taken from a point where dredging had been in progress, and comprised disturbed ground, but the second sample, obtained from another part of the site, where there had been no dredging, was relatively "undisturbed."

That sample was about 3 feet long, and tests were made along the length of the core. The results showed that, in general, although there was some variation, the soil was a soft grey, silty clay, with occasional sand layers. The average value of the liquid limit was 46 per cent., and that of the plastic limit 25 per cent., and the range of the liquid limit was between 36 and 56 per cent. The moisture-content of that surface sample was rather higher than the liquid limit. The particle-size distribution indicated a variable quantity of clay fraction, ranging between 7 and 20 per cent., but in the main 80 per cent. of the material comprised particles between 0.2 millimetre and 0.02 millimetre, that was fine sand and coarse silt. Samples tested in compression yielded an average compression strength of about 2 lb. per square inch, equivalent to a surface bearing capacity of something less than ½ ton per square foot. The Author had stated that the silt was known to vary only slightly with the depth, and the behaviour of the test pile driven to a penetration of 87 feet seemed to support that statement.

Alluvial deposits of that kind, a very silty type of clay or clay-silt, presented special problems for piling. It was obvious that pile-driving records could give no information of value for design purposes, as was evidenced by the case to which the Author had referred, of the results in Shanghai, where the pile went down under its own weight and that of a hammer and yet supported a load of 45 tons within one month. An important characteristic of such deposits was the increase in supporting power with time. The only way to get such information was to carry out pile loading or pulling tests after various intervals.

It might be of interest to draw attention to some data published by Dr. K. Terzaghi, M. Inst. C.E., in the Journal of the American Society of Civil Engineers for February 1942 (p. 317), in a discussion of the Progress Report of the Committee on the Bearing Value of Pile Foundations. Those data related to a site in Scotland, where the soil comprised a deposit at least 120 feet deep of brown silty clay, with a liquid limit of between 37 and 45 per cent., and occasionally exceeding 50 per cent. The water-content was very near the liquid limit throughout the depth. The soil was therefore not dissimilar to that at the present site. Terzaghi carried out

pile loading and pulling tests and obtained some very interesting results, which were plotted to show the increase of skin friction with time. Briefly abstracted, a loading test on a timber pile 12 inches by 12 inches and 85 feet long showed that it supported only 27 tons after 2 days; after 8 days the bearing power increased to 46 tons, and after 28 days to more than 90 tons. He also discussed the effect of the length of the pile upon its increasing supporting capacity with time after driving, and the differences between loading and pulling tests on the pile. In summarizing his results Dr. Terzaghi had emphasized that very few data were available for deposits of that kind, and that the field was relatively unexplored.

Mr. Cooling therefore thought that the Author's tests with screw cylinders were very valuable. They not only brought out the improved performance produced by adding extra screws, but in addition they again showed the very marked influence of the time effect, a point to be emphasized. It was interesting that the improvement took place over a period of 10 months in that particular case. The smaller piles seemed to be approaching a maximum at one month, but in the case of the screw pile a very large volume of soil had been disturbed by screwing down 8-foot diameter plates, so that probably longer time was necessary to obtain the increase in supporting power.

In view of the marked increase of skin friction with time shown by those silt deposits, he did not altogether agree with the Author's statement, on p. 17, *ante*, that the supporting power contributed by the cylinder was probably of a very minor character. Perhaps it was not as great as that of the screws themselves, but he did not think that it would be negligible.

**Mr. S. Packshaw** observed that piling in its various forms had provided generations of engineers with an inexhaustible topic for discussion, mainly because the very uncertainties of the subject had permitted each engineer to stick to his opinion. The divergence of views was well illustrated in *Fig. 1*, which showed that even the Hiley formula, generally accepted in Great Britain, and the "Engineering News" formula, much used in America, could give results that differed by something like 100 per cent. The Hiley formula had a sound theoretical basis, and even the various coefficients which were incorporated in it were derived mainly by observation or by logical reasoning. Unfortunately, that formula was derived from laws governing the impact of semi-elastic bodies, and could therefore take little account of the subsoil, which must ultimately absorb the loads imposed upon it. The process of pile driving was usually completed in a few minutes and if the soil adjusted itself equally quickly, then he thought an impact formula was quite reliable. With the Hiley formula he would, in such circumstances, not hesitate to work to a factor of say 2, or perhaps  $1\frac{1}{2}$ , depending on the conditions of loading and subsoil. Those conditions would be realized in permeable cohesionless material such as sand or gravel. In clays or silts time became a very important factor. Days or weeks might elapse before the surface friction had recovered its original value;

an extreme example of that process had been cited by the Author. On the other hand, the resistance at the lower end of the pile might diminish considerably when the excess water had been squeezed out from the pores. In such circumstances he did not think there was any reliable alternative to the method which the Author had applied, though he agreed that it should be used in conjunction with the Hiley formula. In any case, he would suggest that the carrying capacity of a pile foundation should always be considered as a whole, because the value of one pile in a group might be much lower than the carrying capacity of an isolated pile.

On the other hand, he thought that the column strength of a pile wholly embedded in the ground was not important. He had never heard of a pile failing by buckling, and it could be proved theoretically that the strut value of the pile need be considered only if a large portion of the pile was exposed or if the material into which it was driven was soft clay.

The Author had overcome a very difficult problem in designing the screw-pile jetty in very soft ground as indicated in Fig. 8, Plate 1. Mr. Packshaw was not quite so clear about the reasons which led to the adoption of screw piles for the wharf shown in Fig. 9, Plate 2, where they were used in conjunction with connecting pipes. He thought that in subsoil of good bearing value and with plant already available for driving the composite piles, some form of reinforced or steel bearing pile would have been quicker and more economical.

He had had some experience of sheet-pile construction, and some years ago had prepared several sets of graphs from which the essential information, such as the bending moment, the penetration, and so on, could be read off directly. He wished to commend the Author upon his recognition of the practical and theoretical research carried out by Stroyer. Flexible walls supported by tie rods near the top deflected much more at mid-span than at the supports and therefore permitted much greater strains to be developed in some parts of the backfill than in others. The result was a redistribution of stress which caused a concentration of load at the supports and a reduction near mid-span. Stroyer's work had revealed a great deal about the relation between the angle of friction of the material and the reduction of bending moment. Unfortunately similar information had not so far been available in regard to clays and other cohesive materials. Many sheet-pile walls were built every year, and their very flexibility made it easy to take accurate measurements. For example, a deflexion of 2 inches was not uncommon. Much useful information could be obtained from that measurement alone, apart from others which suggested themselves. There was the opportunity for simple yet fruitful research if provision were made for it when a wall was being designed and built.

**Mr. A. W. Skempton** said that the Paper not only described a successful method of providing foundations for heavily loaded structures on very soft ground, but also showed the logical historical development of that method from the simple driven piles. A knowledge of the historical back-

ground was always helpful in understanding principles, and it certainly added considerably to the interest of a Paper.

The results of the loading tests on the screw cylinders were very valuable records.

There were two distinct sets of results. Firstly those which showed the increased bearing capacity obtained by adding extra screws to a cylinder, and secondly those dealing with the increase in bearing capacity with time.

From a first glance at Fig. 8, Plate 1, it was rather puzzling to see how the screws could make any great difference to the bearing capacity of the cylinder, as they appeared to project only a short distance out from the wall. The answer was, of course, that the area of an 8-foot diameter circle was seven times the area of one of 3 feet diameter; and the addition of a second screw nearly doubled the bearing-area.

The actual increase was 86 per cent., and the addition of a third screw causes a further increase of 45 per cent., the new total area being 172 per cent. of the area of a single screw.

With those values in mind it was interesting to examine the loading-test results in Fig. 6, Plate 1. Mr. Skempton had endeavoured to estimate the loads at which appreciable yield occurred, that was to say, the loads at which there was an appreciable increase in the rate of settlement, and it appeared that those loads were roughly 70 tons, 120 tons, and 150 tons for the single-, twin-, and triple-screw cylinders respectively. Those showed increases of 70 per cent. and 115 per cent. in comparison with the area increases of 86 per cent. and 172 per cent.

Thus the observed increase in bearing capacity was less—and for the triple screw substantially less—than the area-ratios would indicate; and there were perhaps two reasons for that.

Firstly the third screw was situated at only one-half the depth of the lowest screw, and it was certain that the bearing capacity of silt increased to some extent with increase in depth. Secondly the influence of skin friction had, so far, been neglected. That was small immediately after screwing the cylinder, but even so it would probably amount to,<sup>1</sup> say, 75 lb. per square foot. Using that value, and assuming it acted only over the upper portion of the cylinder above the screws, the loads carried by the screws themselves became 56 tons, 108 tons, and 142 tons. The increases were then 93 per cent. and 154 per cent., which were reasonably close to the area-ratios of 86 per cent. and 172 per cent., especially when the reduction in bearing capacity with decrease in depth was taken into account.

The conclusion was, therefore, that the additional second and third screws were almost wholly effective; and that pointed to the very efficient manner in which they increased the bearing capacity.

The second point, concerning the increase of bearing capacity with

<sup>1</sup> From analogy with results quoted by K. Terzaghi. Proc. Amer. Soc. Civ. Eng., vol. 68, 1942, No. 2 (February), p. 319.

time, had been mentioned by Mr. Cooling, and it was a phenomena of great practical importance. From the results given in the Paper<sup>1</sup> it was possible to estimate that increase, which was roughly 90 per cent. in the first 10 months after placing the cylinder.

Those increases were large, but they were entirely consistent with the properties of soft clays and silts. Those sediments were deposited with their particles in a very open structural arrangement, and the weight of the overlying layers, which collected very slowly—probably at a rate of not more than 1 foot or 2 feet in a century<sup>2</sup>—caused a gentle consolidation without any rearrangement of the particles. If, however, the silt was disturbed by the entry of a large screwed cylinder, the bonds between the particles were partially destroyed; with two consequences. Firstly there was an immediate drop in strength which, as many experiments had shown, might quite readily amount to, say, 40 per cent. Secondly the silt started consolidating under its own weight and under the pressure imposed by the cylinder. That reconsolidation caused progressive increase of strength in the silt and by the time equilibrium had been established, a process which would usually take many months, the strength might be 20 per cent. higher than the original undisturbed value.

Thus immediately after placing the cylinder the bearing capacity of the silt was represented by 60 per cent. of its original value; but ultimately the bearing capacity would be represented by 120 per cent. of its original value; and a loading test carried out immediately after placing the cylinder would give a result which was only half that obtained many months later, just as the Author had proved by his tests.

That increase in bearing capacity was obviously extremely useful; but the question arose as to the number of cases in which it could be relied upon, for it was not often possible to wait many months to do a loading test, before deciding on the design.

The increase with time was almost certainly associated with the drop in strength caused by disturbance, and Mr. Skempton did not remember any soft clay or silt which did not exhibit that property; and usually the drop in strength was very marked. From that it seemed probable that an appreciable increase in bearing capacity was the rule, and not the exception, in those sediments, and there seemed to be little reason why it should not be relied upon, to a limited extent, in the design of cylinders.

In the case of driven piles that increase of bearing capacity with time was of controlling importance in soft clays or silts, and rendered any pile-driving formula almost useless.<sup>3</sup> For not only was there a drop in strength

<sup>1</sup> On pages 16 and 17, and Fig. 6, Plate 1.

<sup>2</sup> Hilary Moore, "The Muds of the Clyde Sea Area. Journ. Marine Biological Assoc. 1931. Vol. 17, No. 2 (June), p. 350.

<sup>3</sup> K. Terzaghi, "The Science of Foundations." Trans. Amer. Soc. Civ. Eng. 1929. Vol. 93, p. 287.

caused by disturbance, but also the skin friction was reduced almost to zero by the lubricating effect, of water which was forced out of the soil.

In a comparatively short period that water was absorbed by the soil, and the skin friction was partially restored, whilst after a rather longer time the reconsolidation process was completed, and the bearing capacity of the pile might then be several hundreds per cent. greater than immediately after driving. The neglect of that effect was clearly uneconomical ; but before it could be used with confidence more field observations were needed, of the type made by the Author on his cylinders, and Mr. Skempton wished to emphasize the value of such field records.

**Mr. G. P. Manning** observed that some of the conditions on the site could not be accurately expressed in mathematical terms ; the age and state of mechanical repair of the actual pile-driving plant, the personal skill of the pile-ganger and of the winchman operating the plant, etc. On several occasions people had asked him to give an opinion on the bearing capacity of a pile. The usual data were supplied—a certain pile of a certain length driven through a certain soil, with a certain monkey, etc.—and he was asked to say what safe load he thought that pile would take. His reply to all such questions was the same. If he could visit the site and see the driving he could at once estimate the safe load, but otherwise he would in no circumstances venture an opinion.

In jetty work one often got a pile with a long unsupported length. A pile of that type might stand up to a very heavy sharp blow, but might buckle because of its length under a comparatively small steady load.

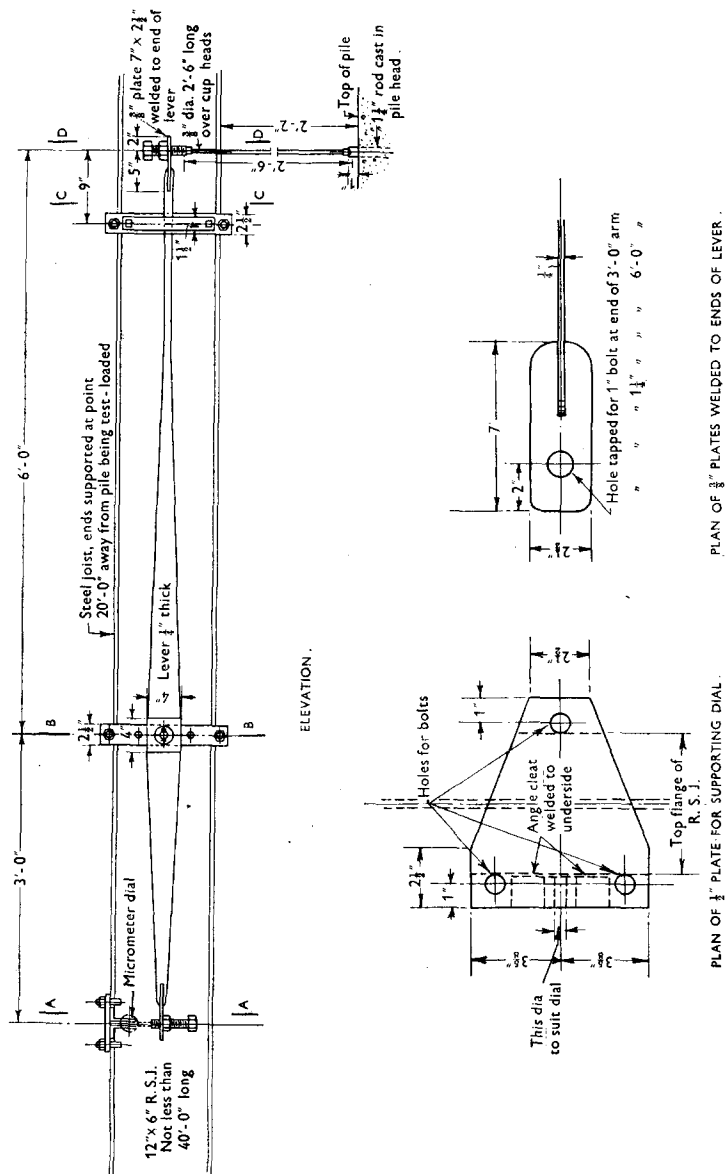
On a fair-sized contract there was no need to rely entirely on pile-driving results. A test-load could be put on the piles in the same way as upon the cylinders. Some years ago his firm were asked to carry out some loading tests on piles, and they used the device illustrated by *Figs. 14 and 15*, which had worked extremely well. The original design had a thin flexible vertical rod, but that was replaced by the push rod on the suggestion of Mr. K. G. H. Montgomery Smith, M. Inst. C.E. The apparatus presented the following advantages :—

- (1) The registering dial was clear of the load, and it was not necessary to crawl about under the kentledge to get readings.
- (2) It was permanently in place and furnished immediate readings for every increment in load.
- (3) The dial was graduated to 0.001 inch, so that the arrangement had a theoretical accuracy of 0.002 inch. After allowing for variations in air-temperature it was certainly accurate to within 0.005 inch.

The illustrations in the Paper indicated that the cylinders deviated from the straight line. What was the approximate extent of the deviation ? Further, the Author had not stated the speed at which the cylinders were driven, nor the depth of the toe of the cylinder below the surface of the ground when the test-load was applied.

Mr. J. Bickley observed that he had found the Paper of particular interest because a substantial part of it was devoted to a form of construction which had for many years been a speciality of the firm with which he

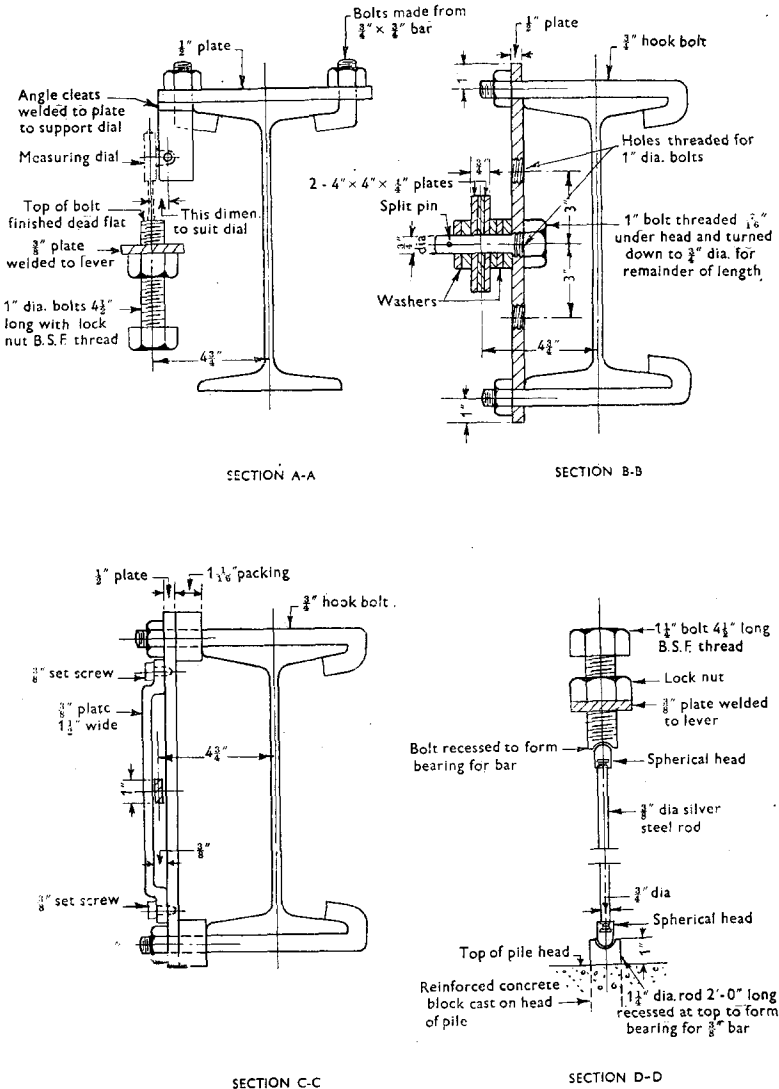
Fig. 14.



was associated and which had been responsible for many developments in the construction of screw-pile foundations and plant for use on such work.

In connexion with the use of reinforced-concrete screw cylinders, known commercially as "Screwcrete" cylinders, the Author had touched upon

Fig. 15.



the problem of screwing cylinders of large diameters provided with screws having closed ends. In the past it had been taken for granted that a pile of comparatively small diameter provided with a solid nose would penetrate without difficulty, whereas a cylinder of large diameter would, in similar circumstances, refuse to penetrate unless the screw had an open end to enable the core to be removed from the interior of the cylinder. This was not a reasonable supposition provided the design of the large screw was simply a large-scale model of the smaller screw, although one would expect the screwing torque required to drive the larger screw to be correspondingly greater. The difficulty experienced in obtaining satisfactory penetration by cylinders of large diameters with closed ends had been largely due to the fact that such screws had not always been true large-scale models of smaller screws. The designer had been mainly concerned with limiting the screwing torque as far as possible, and had endeavoured to do so by reducing the blade-diameter to the bare minimum required to provide bearing capacity, and by using a correspondingly small pitch. The result had been that the ratios of blade-diameter to boss-diameter and pitch used in the design of large screws had been very different from those used in the design of smaller screws, and therefore an open end had been necessary to ensure satisfactory penetration of the former.

The continued success of screws with open ends could be attributed largely to the efficiency of water-jet and air-lift apparatus, which provided a rapid means of removing the core from the interior of the cylinder. That apparatus was first used in connexion with the screw cylinders which formed part of the piers of a number of plate girder bridges constructed on the South Indian Railway in 1926 and 1927.

The development of the Screwcrete type of screw cylinder brought with it the problem of making the interior of the cylinder watertight, a condition which was difficult to obtain when the screws had open ends. When the trial cylinders for the new Brooking Street wharf were put down at Rangoon, in 1936, the Chief Engineer to the Port Commissioners objected to large quantities of the river-bed being removed by the use of the water-jet and airlift apparatus referred to above, and there was therefore no alternative to the use of screws having closed ends. The screws were designed with a blade/boss-diameter ratio of 2.3 : 1 and a blade-diameter/pitch ratio of approximately 4 : 1, proportions corresponding closely with those generally used for smaller pile screws. As expected, the screwing torque attained fairly high values, and built-in water jets were provided in the noses of the screws to keep the torque within the capacity of the screwing-plant. The use of built-in water-jets had in the past been regarded with considerable disfavour, since the conventional type of jet was liable to become choked very easily under working conditions and could not be cleared without great difficulty. Consequently the greater part of the screwing might have to be carried out without the assistance of

the jet. On the work at Brooking Street, however, that difficulty was overcome by the adoption of a simple type of non-chokable jet devised by the contractors' resident engineer. Experience with a satisfactory type of built-in jet had proved that, if the screws were properly proportioned, it was a comparatively simple matter to drive screws of large diameter provided with closed ends in any strata for which screw piles of any other type were suitable.

The Author had drawn attention to the magnitude of the loads which were likely to be imposed on the supporting cylinders when the screwing-machine was carried on the completed portion of the structure. Mr. Bickley wished to suggest that the greater part of that load was due to the fact that cylinders weighing between 15 and 20 tons might have to be pitched at least one bent ahead of the cylinders supporting the plant. If, therefore, the plant were mounted on the completed portion of the structure, the maximum loads which were imposed on the latter would be of considerable magnitude, irrespective of the type of plant used. In any case the application, during construction, of a load approximating to the permanent load need not necessarily be regarded as a disadvantage.

**Mr. J. E. G. Palmer** wished to inquire whether the large open-ended screw-cylinder had any tendency to deviate from the plumb when it met an obstruction.

Fig. 9, Plate 2, showed piles raking at the rake of 1 in 2; that was rather an unusual rake, and he would be glad if the Author would state whether he had used any particular method for driving those piles. The Paper conveyed very clear descriptions of the method of constructing screw-piled jetties, usually by the over-end system. The advantage of the ordinary timber and pre-cast concrete pile was that a floating pile frame could be brought on to the job and the piles driven in quickly. Mr. Palmer was superintending the construction of a jetty in very soft mud, using 15-inch square reinforced-concrete piles, and was hoping to get reasonable sets by casting on a 30-inch square bulge some 20 feet up from the toe; that should produce a more economical job than screw-piling.

The Paper, however, contained no mention of costs. In his most inspiring Address<sup>1</sup>, the President had appealed to engineers to give up being mere technicians and to become planners and leaders. Surely the cost was one of the most important factors in any scheme. The excellent 73 foot jetty illustrated in Fig. 8, Plate 1, was obviously a very fine design; but what had it cost per square foot? Was it the kind of structure that engineers should recommend to their clients in peacetime or was it something they should avoid? Mr. Palmer appealed to all Authors of Papers to give the costs of their jobs.

\* \* **Mr. Leslie Turner** considered that the Author's remarks concerning the dynamic piling formulas would meet with general agreement.

<sup>1</sup> Journal Inst. C.E., vol. 21 (1943-44), p. 1. (Nov. 1943.)

\* \* This contribution was received in writing.—SEC. INST. C.E.

As the only criterion of measuring ultimate pile resistances, even the best formula for any particular case might be misleading, owing not merely to the kinetic losses, which could be measured quite closely with the requisite apparatus, but chiefly to the fact that the condition of the ground during and immediately after driving was not the same as it was after repose and for the remainder of its life, when temporary ground compression had been dissipated and extruded ground-water redistributed. Again, the carrying of an ever-present static load was a different proposition from resistance to an instantaneous shock.

Nevertheless, he thought that a suitable dynamic formula would, perhaps, always serve as an immediate and practical *qualitative* indication on *works*, as measured "sets" did give a simple picture of relative resistance which could be understood by piling foremen.

Since it was the *ground* that eventually carried the load, irrespective of the type of pile used, he preferred, when possible, to base the ultimate resistance on, or at least to check it in the office with, the static formula comprising: (1) the direct and bearing resistance, and (2) the side frictional resistance.

Unit values for those factors could be assessed from borings, but that involved conjecture and might be as faulty as the dynamic method. That criticism could be avoided if the end bearing and frictional values were measured separately by appropriate site static load-time testing apparatus. There again, correct interpretation of results was necessary, together with allowances to compensate for area differences. In conjunction with soil tests, those would perhaps yield the nearest approach to dependable forecasts.

Probably nothing would ever supersede experience in those matters, and the loading test on a pile might remain the only true confirmation of ultimate resistance; but the nearer the ideal could be approached by pre-testing the ground in a practical way, the greater would be the efficiency of piling technique.

In a poor ground, such as described by the Author, increased resistance had been achieved by the addition of direct bearing resistance afforded by the blades of the screws. Another method of approach that might be used with timber or reinforced-concrete piles in slightly better ground would be to increase the side resistance by the addition of bearing areas provided by notches at intervals in the length of the pile. These notches were eventually filled by the re-expansion of silt or clay into them, brought about by the compression around the pile caused by the forcing in of the point.

Mr. Turner had tried that in a geologically recent deposit of silt which was fairly consistent for more than 100 feet in depth, with the following results:

Two similar 12-inch by 12-inch timber piles were driven to a depth of 30 feet, one with plain sides as normally used, and the other with notches

2 inches wide round the periphery of the pile by 0.6 inch depth, cut 8 inches apart centre to centre. Even during driving, when the notches would probably not be completely filled and the ground would certainly be disturbed, the set of the notched pile at a depth of 30 feet was half that of the plain pile, which by Hiley's formula would indicate an increase in resistance of 55 per cent. due to the notches. After repose it would be reasonable to expect a bigger increase. Unfortunately, circumstances did not permit that static loading and testing of the piles over a period, which was the only reliable means of obtaining solid proof. In the same ground, however, tractive or pull-out tests were made on 6-inch by 6-inch timber piles to ascertain the frictional value of the silt against timber at various depths, and to relate it to the pulls from notched piles, with inverted notches to engage the ground when pulling upwards. In that case, however, the notched bearing was upwards and was thrusting against an air-surface. Reliance was therefore being placed upon the cohesion or shear of the ground around the pile, and became the limiting factor. That might explain the fact that the increase in pull during extraction due to the notches was only 17 per cent. more than that of the plain pile; but the notched pile brought up the ground around it, whereas the plain pile withdrew fairly cleanly. Moreover the ground had entered and filled up the notches.

Mr. Turner would be very pleased to place his results at the disposal of anyone who had the opportunity to experiment on those lines—it was quite a simple matter to cast those notches in reinforced-concrete piles.

**The Author**, in reply, accepted Mr. Wentworth-Sheilds's correction concerning cast iron; but there were many different grades of cast iron. He believed that commercially pure cast iron did not corrode at all. Possibly, therefore, it was a question of degree. In general he thought that cast iron might be expected to stand up better than structural steelwork. That might perhaps be due chiefly to the greater exposed area per unit volume.

With regard to Fig. 6, Plate 1, there was without doubt breakdown of the first cylinder with one screw. It was impossible to say whether the movement had entirely ceased with the two-screw cylinder, but that cylinder was tested very shortly after being screwed, and it was known that an increase in its bearing capacity was to be expected in time because the second screw was in ground which had been thoroughly disturbed by the passage of the first screw. One could not expect to develop the bearing value of the upper screw for some time.

He had not mentioned the results of the examination of the samples because he had understood that Mr. Skempton and Mr. Cooling were to furnish them.

He agreed with Col. Knight that there was no reason why larger screws should not be used, but it had been definitely established that the diffi-

culties of assembly and of screwing increased rather rapidly with the diameter.

He could not agree that the increase in bearing capacity of the two-screw cylinder was about 50 per cent. higher than that of the single screw, because the latter had definitely broken down. Exact figures could be obtained only when the time-settlement curve showed that movement had entirely ceased. His own opinion was that the increase was more nearly a *pro rata* increase on the effective screw-area so far as could be judged from the diagrams. Mr. Skempton had also referred to that point and had supplied some useful figures.

The answer to the question of different types of ground was clearly indeterminate unless the lower screw were breaking down, in which case the movement should mobilize the full bearing value of the screw at the higher level, which was  $1\frac{1}{2}$  ton per square foot. If the lower screw carried, less than 5 tons per square foot the upper screw would develop some indeterminate fraction of  $1\frac{1}{2}$  ton per square foot.

He had been rather interested in the suggestion of a floating structure, but he thought the answer was probably to be found in the quantity of steel required and in the heavy works required to keep such a structure stationary in the case of a berth for large sea-going vessels. Mr. Du-Plat-Taylor had said that the power required appeared to be 5 horse-power per screw. That was not the case. The increase was about 5 horse-power for each screw additional to the first, but the latter required more power.

The suggested use of large cylinders in order to take advantage of their buoyancy was interesting, but if they were to be screwed it would be of necessity with an open end. They would have to be made watertight after screwing. Some practical difficulty might arise in waters where there was much rise in tide, because a variable force due to buoyancy would be exerted, and that would require to be considered carefully in the design.

In reply to Mr. Wilson, in order to shorten Fig. 6, Plate 1, which was very long in point of time, extending over more than 200 hours, a cut had been made. The level at 110 hours was, of course, higher than the level at 180 hours. Again, the loading diagrams coincided for the double- and triple-screw cylinders for a short time between 75 tons and 100 tons. Such difficulties could not be avoided with superimposed diagrams.

The information given by Mr. Cooling was very interesting. The improvement which had taken place at the end of 10 months was known, but it might have been established before that period expired, or it might have continued and have become even greater in 15 or 20 months. Probably a 90-per cent. increase in 10 months was very nearly correct.

He concurred with Mr. Packshaw's remarks on the Hiley formula, and agreed also that it would be reasonable to use a factor of  $1\frac{1}{2}$ –2 with that formula in some circumstances.

With regard to Fig. 9, Plate 2, the reason for using cylinders was that the loading in that case was unusually heavy at the front of the wharf.

One of the sheet-piled wharves had played its part on one occasion with some success, when a surcharge of 18 cwt. per square foot had been carried. That seemed to him worthy of remark.

He agreed with Mr. Skempton that friction would play some part and that the bearing value would increase with depth; but he believed that it would not be correct to assume that the friction between the cylinder and the ground was of the same order as the actual shear strength of the silt.

In reply to Mr. Manning, the cylinders, or some of them, were out of plumb to a certain extent.

With regard to Mr. Bickley's point, it was true that the weight of the screwing-machine was not necessarily a disadvantage, but it could be when it involved the use of heavy temporary bracing of the cylinders. At such times the use of a cage and capstan was to be preferred. On the other hand, there were occasions when the weight would be of advantage.

In reply to Mr. Palmer, the Author did not know of any case which indicated definitely that the open-end cylinder was more likely than the cylinder with a closed end to run out of plumb.

The raking piles were driven after the vertical piles. Leaders were placed at the correct angle at deck-level and the piles were pitched and driven in that way through an opening in the deck.

The difficulty in screwing from a barge lay in locating the cylinders accurately, and it was necessary to be rather more accurate relatively than in the case of piles. It was preferable to use a cage if possible.

He regretted that circumstances prevented him from giving any information in regard to costs.

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Paper No. 5409.

### **"The Moment-Distribution Method."†**

By JOHN ARTHUR TODD, Ph.D.

*(Ordered by the Council to be published with written discussion.)*

THE object of this Paper is to show that the method of successive approximation due to Professor Hardy Cross<sup>1</sup>, and known as the moment-

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† Correspondence on this paper can be accepted until the 15th June 1944, and will be published in a Supplement to the Institution Journal for October 1944. Contributions should be limited to about 600 words.—Sec. INST. C.E.

<sup>1</sup> "The Analysis of Continuous Frames by Distributing the Fixed End Moments." Trans. Amer. Soc. Civ. Eng., vol. 96 (1932). See also Southwell, "Relaxation methods in Engineering Science" (Oxford, 1940), p. 101.