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WHAT HAS BEEN LEARNED ABOUT DRILLED SHAFTS FROM THE OSTERBERG LOAD TEST

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Summary

The Osterberg (O-Cell) Method makes it possible to separate the side shear resistance (skin friction) from end bearing. The O-Cell is placed on or near the bottom of a drilled shaft and after the concrete is poured and cured, an equal upward and downward pressure is applied. From the test, the load-upward deflection curve in side shear and the load-downward deflection curve in end bearing are drawn. Typical curves are shown where the ultimate load in side-shear is reached and where the ultimate load in end bearing is reached. Several examples of tests in which the test load reached ultimate loads far in excess of what was expected are shown. The side shear in rock sockets is shown to be much larger than generally estimated. Examples are given of where side shear is smaller than expected and the reasons discussed. Disturbance of the sides of drilled holes due to poor construction techniques and ways to avoid these conditions are considered. Examples of bottom hole disturbance are given and ways to prevent the disturbance are discussed. A graph showing the actual measured capacity of drilled shafts compared to the estimated capacity as a function of the hardness and strength of the soil or rock is presented.

Introduction

Approximately 400 load tests have been made with the Osterberg Load Cell (O-Cell) in 13 countries. Because the O-Cell test separates end bearing and side shear (often called side friction) and provides separate load-deflection curves for side shear and end bearing, it is possible to determine at each increment of load how much of the total load is in side friction and how much is in end bearing. Because the deflection of the shaft is small when the ultimate load is reached in side shear compared to the deflection at which the ultimate end bearing is reached, the majority of the load is taken in shear as the load is applied and shifts to end bearing as the load is increased. For many cases, where the soil profile is relatively uniform throughout the depth of the shaft, the great majority of the load (70-80%) is taken in side shear at the working load. If the shaft penetrates through a relatively soft soil with end bearing on a much harder soil, the side shear still develops first, but when the working load is reached, the end bearing may take the majority of the load.

In rock sockets, the side shear also develops faster than the end bearing as the load is increased. Based on tests in rock sockets of different types of rock and in both strong and weak rocks, the side shear is found in most cases to be much larger than is generally assumed by the design engineer. In relatively few cases for shafts in soil and in rock sockets, side shear surprisingly is smaller than expected. The reasons for this are discussed for specific cases.

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The O-Cell load-deflection curves make it possible to determine approximately how much disturbance is on the shaft bottom and how it influences the working load and so-called factor of safety.

The Osterberg Load Test Method

Fig. 1 shows a hydraulic jack-like device placed on or near the bottom of a drilled shaft. After the concrete is poured (tremie concrete if the hole is stabilized with slurry) and cured, hydraulic pressure is applied to the O-Cell which exerts an equal upward and downward force on the shaft. The force is determined by recording the pressure and converting it to force from a pre-determined calibration curve. The downward force is resisted at all times by the side shear (skin friction) and therefore no overhead load frame with hold down piles or a dead weight reaction is needed. The pressure, the upward movement of the bottom and top of the shaft, and the downward movement of the bottom of the shaft are measured by telltales and/or strain gages and are recorded on a data logger from which the movements can be plotted and/or shown directly on the screen. Movements will continue until either the ultimate in side shear, the ultimate in end bearing, or the capacity of the device is reached, whichever occurs first. When this occurs, the test is completed. For the largest capacity size O-cell (three feet diameter) the maximum force which can be applied is 3,000 tons up and 3,000 tons down. For large diameter shafts, three O-Cells have been used, capable of exerting a total of 18,000 tons (upward *plus* downward). The stroke of the piston on all sizes of cells is 6 inches, though a larger or smaller stroke can be provided. A method of constructing the equivalent top-down curve is described by Osterberg (1998). Also shown in that reference is evidence that the side shear acting downward as in the O-Cell test is the same as the side shear acting upward as in a conventional top down test, Ogura (1996). Recently, in Singapore, a conventional kentledge test (dead weight reaction) was made nearby an O-Cell test on shafts 4 ft. in diameter and108 ft. depth with a maximum load of 3,200 tons. The result showed good agreement between the two

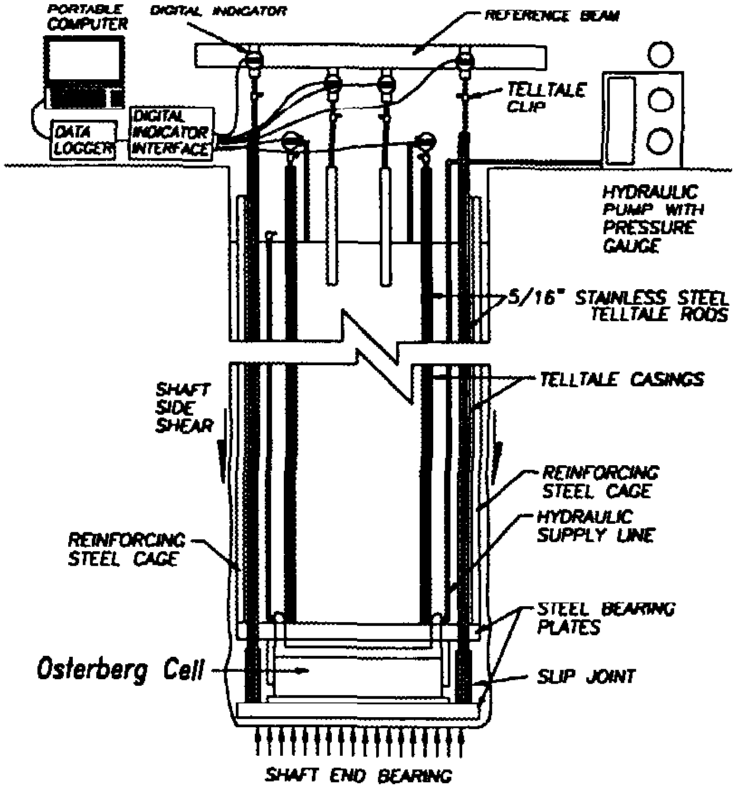

Figure 1 - Osterberg Load Test Method

methods even though the load increments and holding time of the increments differed considerably.

Approximately 400 O-Cell tests have been performed. Loads of up to 15,000 tons have been made on shafts up to 9 feet in diameter and up to 200 feet deep. Tests can be made with any increment of load, held for any time interval and can be reapplied any number of times. A full-scale test is still under way in which side shear is being *measured at monthly intervals for over two years.* Many tests have been made off-shore, in deep water.

Typical Test Curves

Fig. 2 shows test results in which the ultimate load in end bearing is reached. Note that at 1,350 tons the downward movement of the shaft in end bearing is almost 4 inches and at the same load the upward movement of the shaft is 0.01 inch. Thus, if the working load is anything less than 1,350 tons *virtually all the load is taken in side shear.*

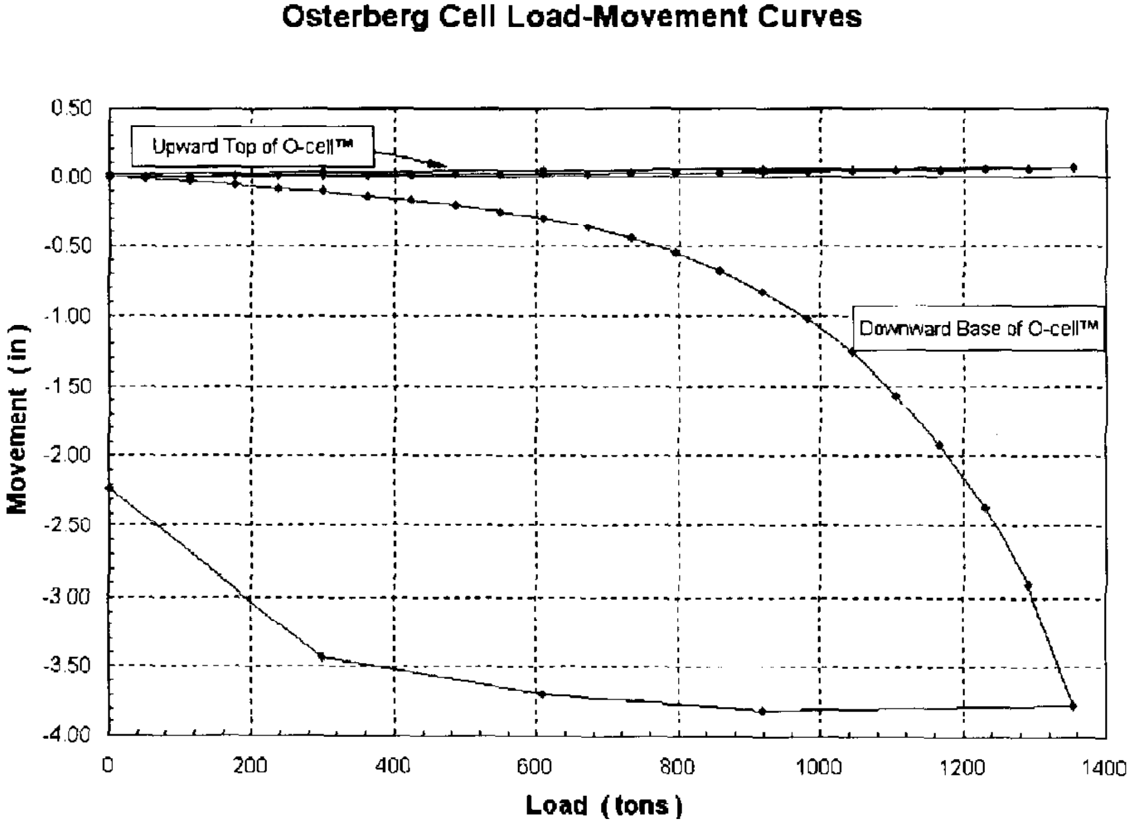

Figure 2 - Test where Ultimate Load Occurs in End Bearing – *(virtually no upward movement of shaft)*

Fig. 3 shows test results in which there is virtually no movement in side shear at 250 tons and over 5 inches downward movement in end bearing.

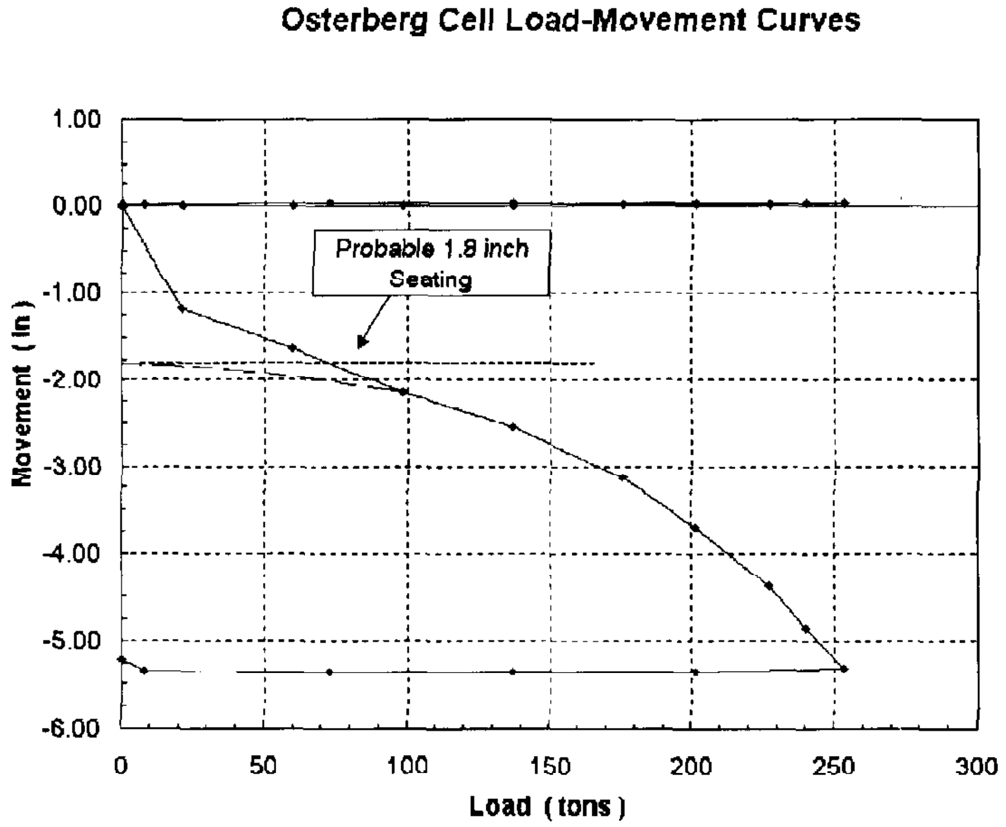

Figure 3 - Example of Large Initial Settlement due to Soft Bottom

If there were little or no disturbed soil at the bottom, the end-bearing curve would have the shape shown in Fig. 2 where the deflection gradually increases for each equal increment of load. However, It is seen in Fig. 3 that there is large movement at initial increments of load. If the shape of the curve for undisturbed bottom is extrapolated to zero, it is seen that the depth of disturbed or/and soft material is about 1.8 inches. Tests have been made where the estimated thickness of disturbed soil was as much as 5 inches. The number of tests with large initial compression due to soft material on the bottom is relatively few. However, it is believed that in a very large number of tests, there was some disturbance on the bottom and that the placing of the concrete either displaced the soft material; or, if the thickness of the disturbed material was small, it was compressed by the weight of the fluid concrete before the concrete cured.

Fig.4 shows a test where the ultimate was reached in side shear at about 0.50 inches *and the end bearing deflected about 0.35 inches but was far from the ultimate load. The* small movement needed to reach ultimate in side shear is typical of clay soils and some rocks In some cases such as stiff clays. the movement required to reach ultimate can be as small as 0.25 inches. For sandy soils, the movement required to reach ultimate is usually somewhat larger.

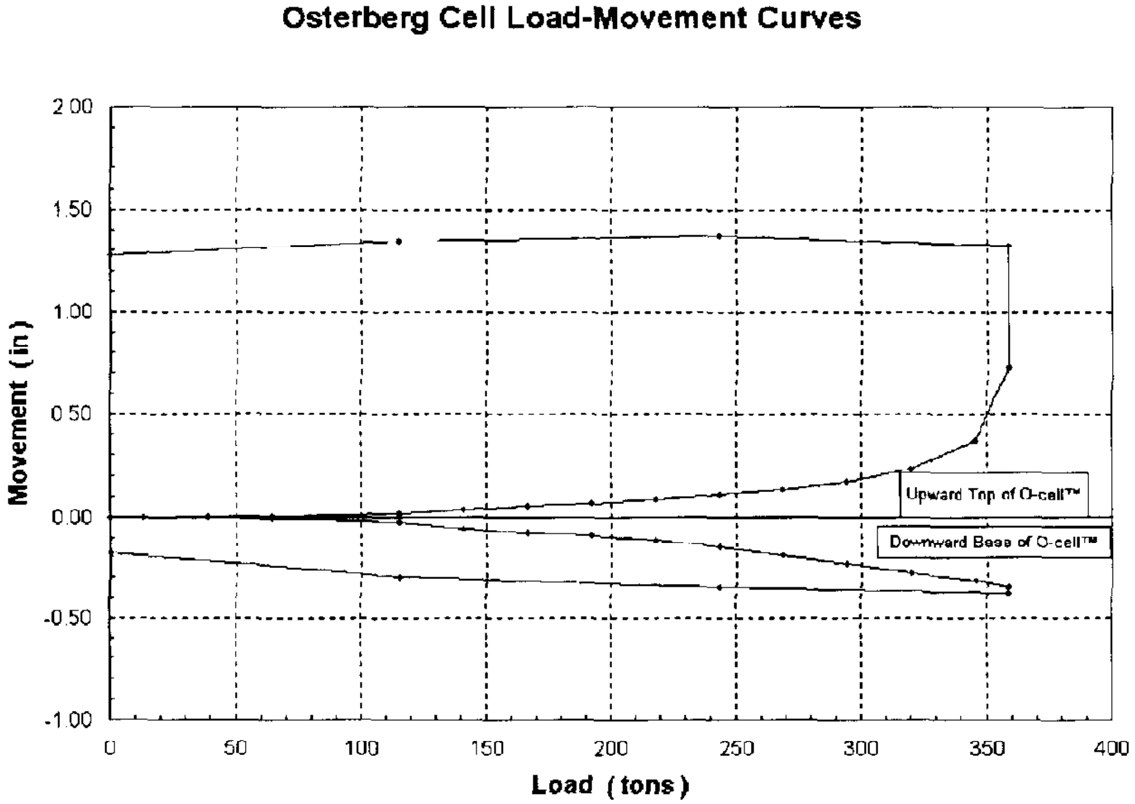

Figure 4 – Test where Ultimate Load Occurs in Side Shear

Notice in Fig. 4 that when the ultimate in side shear is reached, continuous movement *occurs at constant load. This has been observed in the majority of tests.*

Also, on cyclic loading in side shear, the load generally returns to the same ultimate as in the previous cycle. Thus, there is no drop off in ultimate side shear strength with time or with repeated loads. Fig. 5 is an example of this.

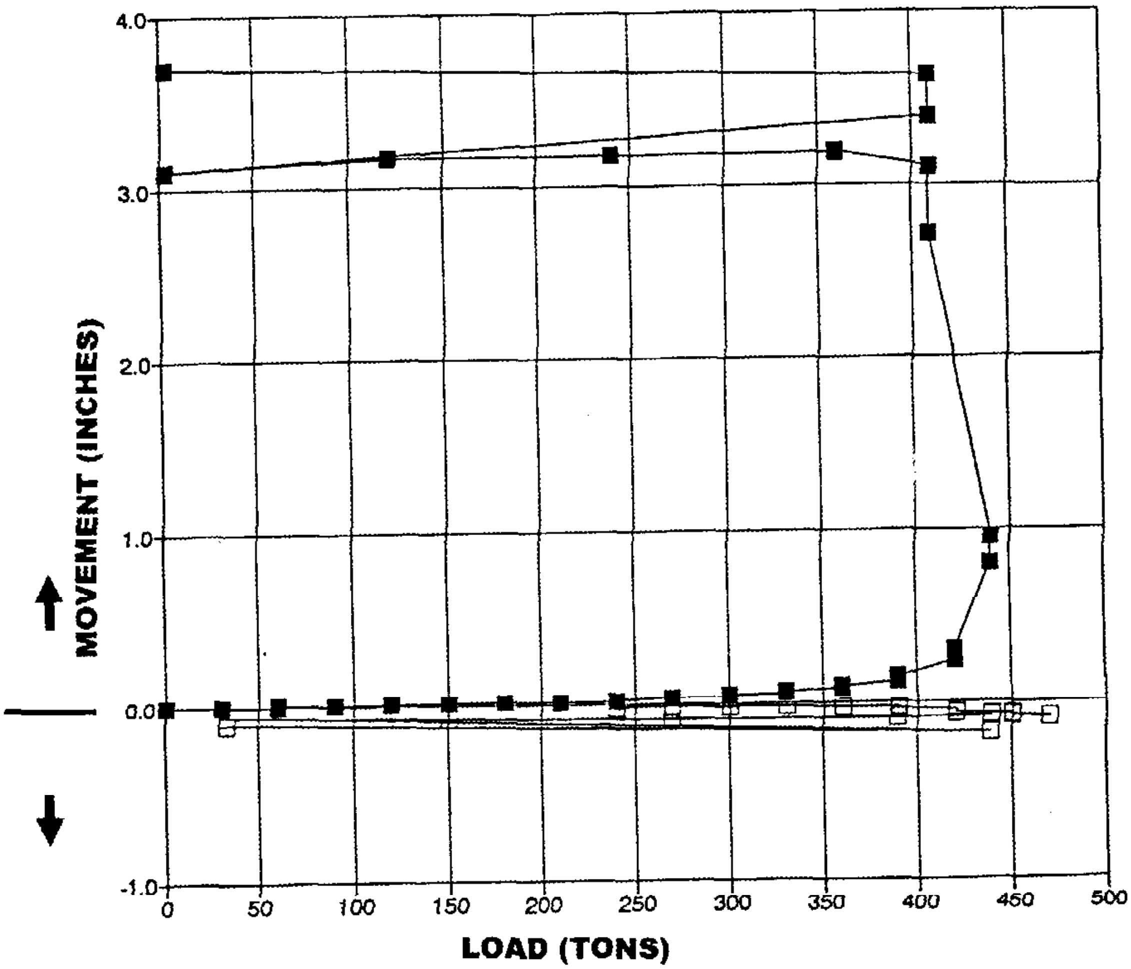

Figure 5 - Example of No Drop off in Ultimate Side Shear Strength with Repeated Loads (from Interstate Route H3 Test, Honolulu, Hawaii)

Drilled Shafts with Rock Sockets

It has been found in the great majority of cases that the ultimate side shear strength for rock sockets has been greatly underestimated. Correlations of compressive strengths of rock cores and unit side shear are frequently not reliable. This is particularly true for rock formations that are laminated such as shales. When shale rock cores are tested, the laminations cause low unconfined strength. In the field, the rock is subjected to the weight of the overburden and therefore the shear strength between the laminations is increased because of the higher normal pressure. The following two cases illustrate how very low estimates of side shear resulted in large over designs.

Fig.6 shows the soil and rock profile and load deflection curves for a test shaft for a bridge over the Ohio River at Owensboro, Kentucky. The rock consisted largely of shale with limestone and coal seams. The compressive strength of the rock cores varied from 350 to 500 lbs/sq in. Because of possible deep scour in the future, only the load capacity of the 19 ft. of shale below the sand was considered in the design. As seen in the figure, concrete was placed to some distance above the rock socket. However, strain gage readings in the concrete showed that the load taken in the shaft above the rock socket was negligible. The test was designed to go to three times the design load of 1,000 tons.

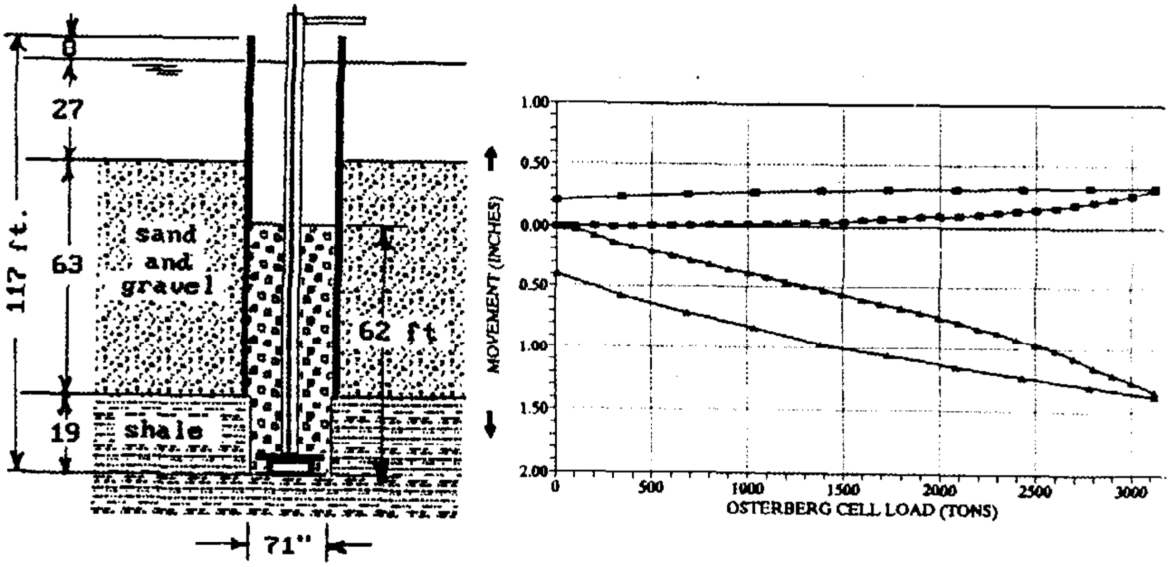

Figure 6 - Test Shaft for Bridge in Owensboro, KY

However, the load went to six times the design load and ultimate load in side shear or end bearing was not reached. The test could not continue to a larger load because the capacity of the O-Cell of 6,000 tons (3,000 up and 3,000 down) was reached. At the design load, the total deflection was only 0.2 inch. When the test was discontinued, the upward movement in side shear was only 0.2 inch indicating the ultimate side shear would have been larger than 3,000 tons.

Fig. 7 shows the load-upward movement and the load-downward movement curves for a drilled shaft for a bridge pier in the Mid-West.

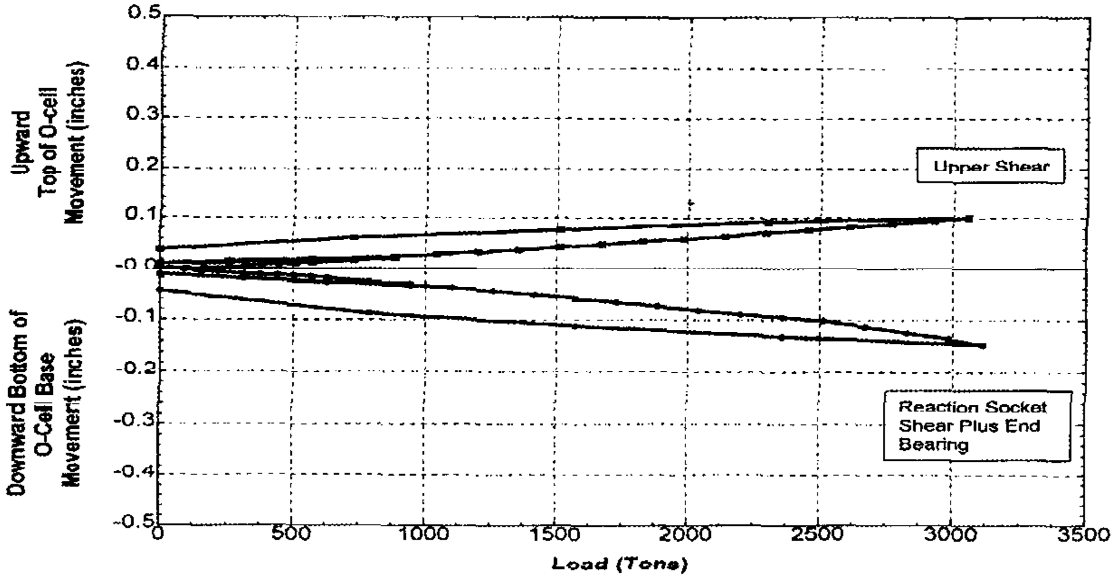

Figure 7 – Test Results for a Drilled Shaft for a Bridge Pier

Fig. 8 shows the equivalent top-down load-settlement curve.

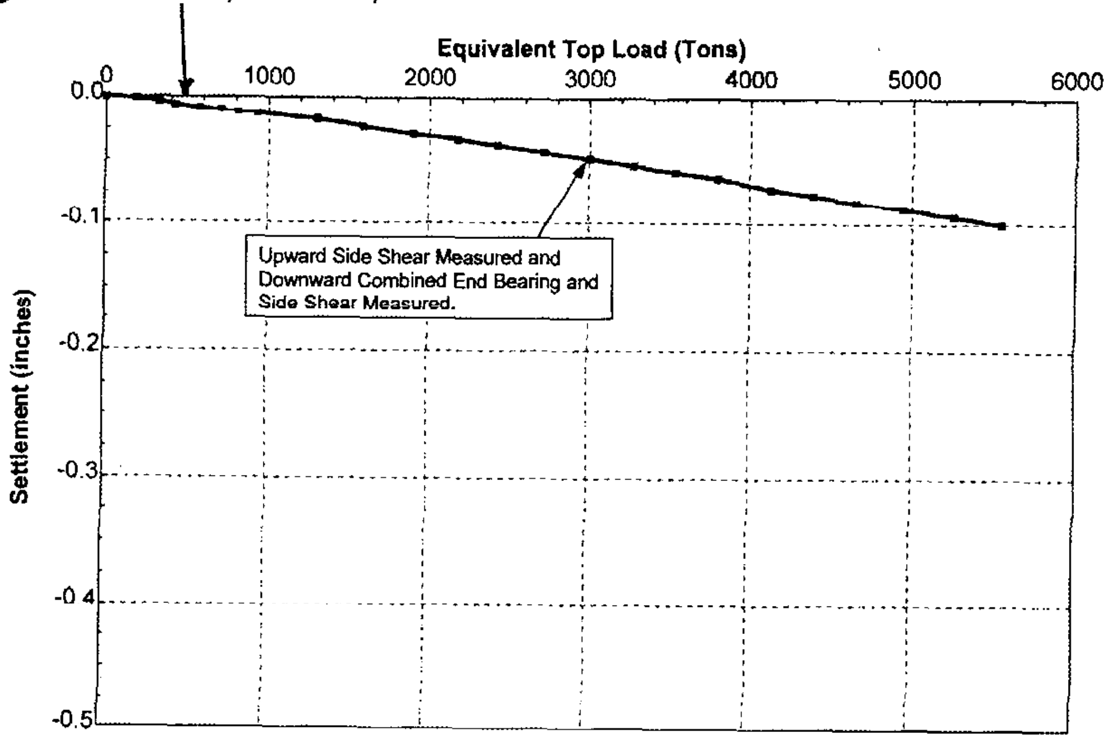

Figure 8 - Equivalent Top Down Curve for Shaft in Fig. 7

The shaft went through the overburden and was socketed in *37 feet* (!) of layers of sandstone/shale, limestone shale, limestone and shale. The design load was 500 tons and the test was made to 6,000 tons (3,000 up and 3,000 down). Here again, the test was discontinued because the capacity of the O-Cell was reached. It is seen that all the curves are linear indicating that neither the ultimate load in shear or end bearing was even approached. At the design load, the movement was only 0.01 inch, which is less than the elastic compression of the shaft would be if the design load were transmitted over the entire shaft. This, of course, indicates that the load is dissipated in side shear only a relatively short distance down from the top and that no load reached the bottom in end bearing. However the design engineer did not take advantage of this information to redesign the shaft.

Disturbance of Side of Hole

Experience with O-Cell testing has shown that in the majority of cases, the ultimate side shear is considerably greater than estimated. However, exceptions have been found, Schmertmann et. al., (1998). In one instance, from a test in Hawaii on a hard saprolitic clay, the side shear was found to be lower than expected. The hole was drilled with a rotating core barrel which it was believed resulted in remolding and smoothing the side of the hole. When drilling was made with a core barrel which was rifled, the side shear increased 50% and the deflection to cause ultimate was only 0.10 inches whereas without the rifling, the deflection at ultimate was 3.3 inches. This clearly indicates the disturbance and remolding of the saprolitic clay and the value of roughening the side walls.

Another exception to the large side shear found in most cases is when drilling in shale and stabilizing the hole with bentonite drilling fluid, the bentonite and/or water can penetrate a short distance into the seams of the shale and cause a mud cake to develop on the shaft wall, thus reducing the side shear strength. To prevent or/and reduce side wall disturbance, the shaft should be tremied as soon as possible after the drilling is completed.

In another case, Schmertmann and Hayes (1997), a hole 3 ft. in diameter and 60 ft. deep in sand and silt was drilled "dry" and stabilized with a casing. The water head at the bottom was 35 feet. The side shear after completion was 450 tons. When a replacement hole was drilled and water in the casing was kept higher than the ground water table, the resulting side shear was 1,900 tons, an increase of more than four times.

These and many other cases have demonstrated that the method and construction techniques used in drilling a shaft has a marked influence on the resulting side shear of the shaft.

Bottom Hole Disturbance

The technique of drilling, stabilizing and cleaning a drilled shaft has a great influence on the disturbance of the bottom of the hole. It has previously been shown in this paper, that bottom disturbance can be estimated from the O-Cell downward deflection curve of the bottom of the O-Cell. There can be many causes of this disturbance:

1. Improper use of the cleaning tools.
2. Use of improper tools for the specific bottom conditions of the hole.
3. Insufficient cleaning with the proper tools.
4. Water seepage into the base of a hole
5. For a slurry hole, incorrect design of the slurry ingredients
6. Contamination of the slurry occurring during drilling, such as sand accumulating during the drilling and the slurry not being desanded during drilling.
7. Allowing the hole to stand idle too long after completing drilling and before placing concrete.
8. Failure to maintain at all times a pressure head inside the hole larger than the pressure head due to the groundwater. Just a drop in head inside the hole for a very short time can cause disastrous consequences.

The effect of poor or improper workmanship in constructing drilled shafts is discussed by Schmertmann et al (1998), and by Schmertmann and Hayes (1997). One example they report is of a dry hole 60 ft. deep in sand and sandy silt. The bottom of the hole was above the water table. The hole was drilled and cleaned out with an auger. The results from the O-cell were so poor than another hole was drilled with the same equipment being very careful to adequately clean the bottom. Fig. 9 shows the load-downward deflection of the bottom for both holes.

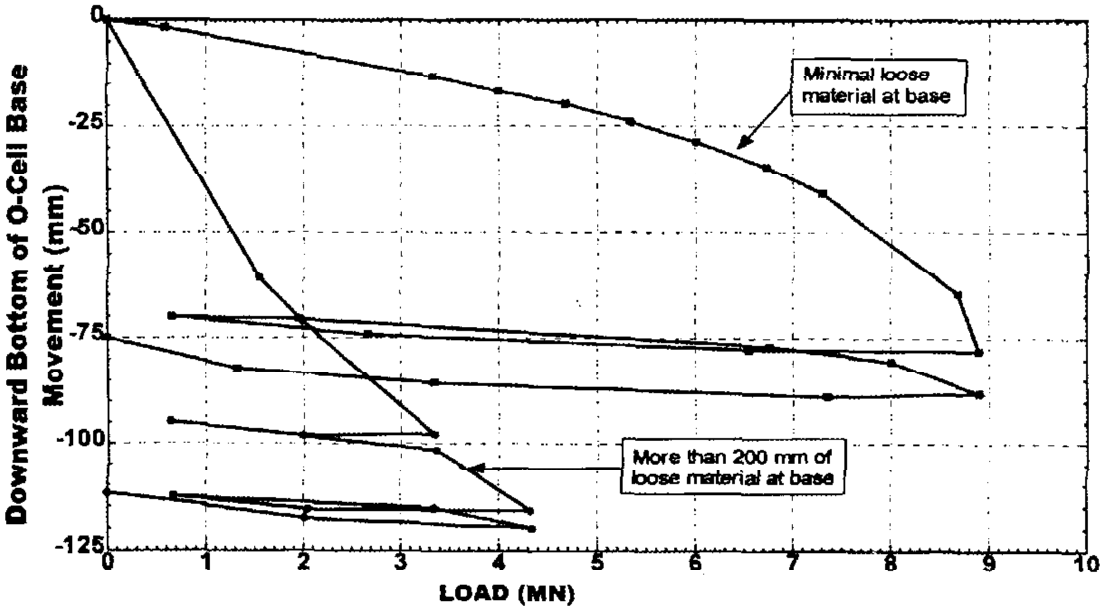

Figure 9 – Effect of Poor Cleanout ("dry hole") in Sands, Gravel

The difference in O-Cell test results is quite dramatic. The number of drilled shafts which have been found to have low load capacities due to poor workmanship or wrong drilling methods is small compared to the number of O-Cell tests which have shown drilled shafts to have load capacities which were as expected, or even much higher capacities than were expected in many cases. By demonstrating what techniques produce little or no side or end bearing disturbance, contractors and drillers can and should be persuaded to adopt these techniques.

Measured versus Estimated Capacity as a Function of Soil/Rock Strength

As shown, in the large majority of cases, the measured capacity of drilled shafts was found to be larger than that estimated by the geotechnical engineer. It has been shown by Schmertmann that the amount by which the excess capacity as determined from O-Cell tests exceeds the estimated strength of the supporting soil/rock, increases as the strength of the supporting soil/rock increases. Twenty- five test results were selected where there was enough information regarding the strength of the supporting medium. For these tests, a comparison was made with the engineer's estimated capacity. It was found that the ratio of the measured to estimated capacity (M/E) tends to increase as the strength of the supporting medium increases as shown in Fig. 10.

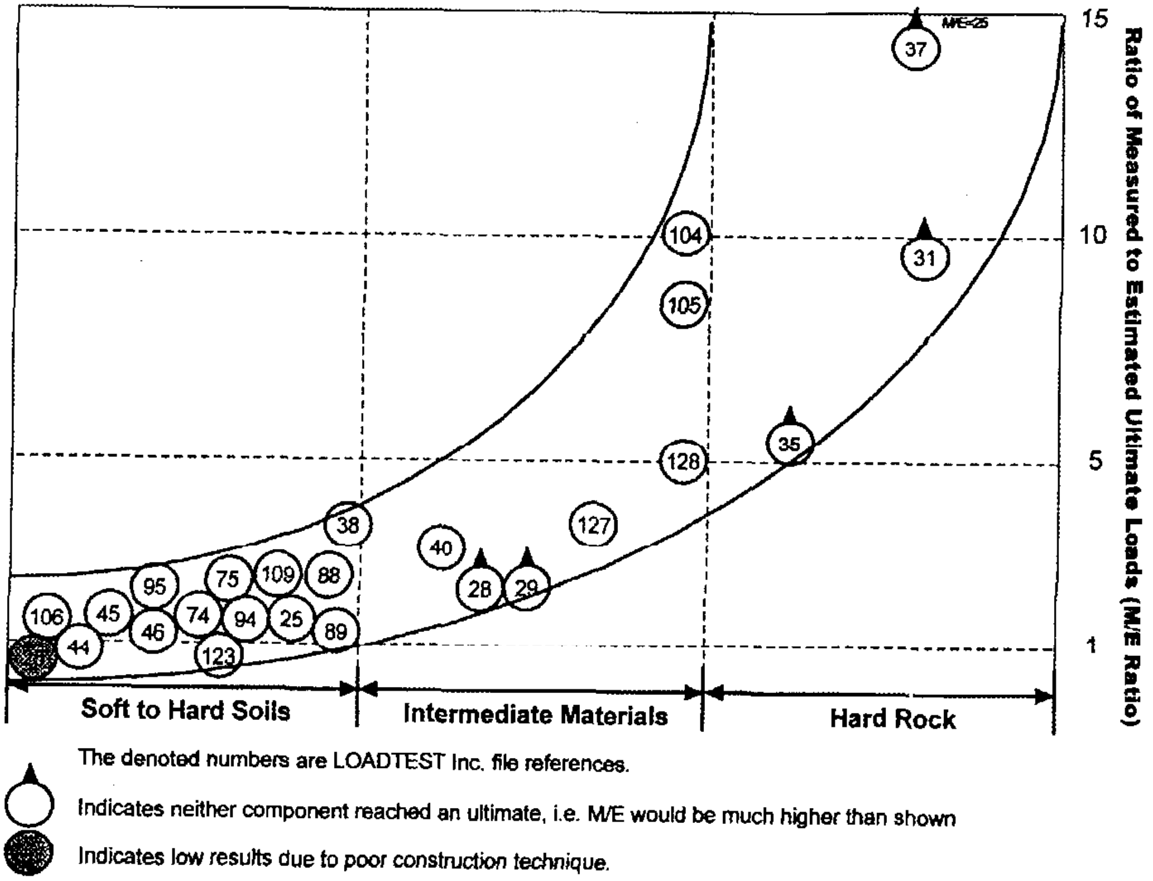

Figure 10 – Ratio of Measured to Estimated Ultimate Loads

It is seen that for soft to hard soils, the M/E ratio varies from 0.7 to 3. For intermediate soils such as coarse sands, dense silts and glacial tills and weathered rock, the ratio increase to about 3 to 5. For hard rock, the ratio is from 5 to 15. Thus somewhat ironically, the harder the medium, the more the load capacity of the shaft is underestimated.

Conclusions

1. The O-Cell method makes it possible to separate end bearing from side shear as components which add up to the total bearing capacity of drilled shafts.
2. Since the deformation required to mobilize the ultimate side shear resistance is small compared the deformation required to mobilize the ultimate end bearing, the side resistance is mobilized first as the load increases and at the working load the side shear generally takes about 70 to 90% of the load. As the load increases beyond the working load, a larger percentage of the load is taken by end bearing.
3. When there is end bearing disturbance, the deformation of the shaft bottom becomes large as the end bearing load increases. When the end bearing load is large enough to compress the disturbed material, the rate of increase of deformation with load is smaller after the disturbed material has compressed enough to transmit the end bearing load to the undisturbed material.
4. In cases where at the working load, the large majority of the load is taken by side shear, the factor of safety against excessive settlement may not be as large as is generally thought. In cases with sufficient disturbed material on the bottom, excessive settlement may occur when a small increase in the working load exceeds the side capacity thus, transferring significant loads to the soft bottom. The deformation of the shaft will increase rapidly as the working load is exceeded, thus reducing the apparent factor of safety against excessive deformation.
5. Disturbance of the bottoms and sides of drilled shafts are usually the result of poor design, poor workmanship and/or improper drilling techniques.
6. Acceptance of and adherence to techniques and workmanship known to result in relatively undisturbed shafts and development of new techniques for drilling and cleaning holes will give engineers more confidence in the reliability of drilled shafts.
7. Side resistance of rock sockets has been shown in general to be much larger than engineers' estimates. Even when this is demonstrated to engineers, they are reluctant to accept the findings and to design rock socket shafts less conservatively.
8. Testing a drilled shaft to ultimate does not "fail" it. The capacity of a drilled shaft after testing is virtually always better than before the test.

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