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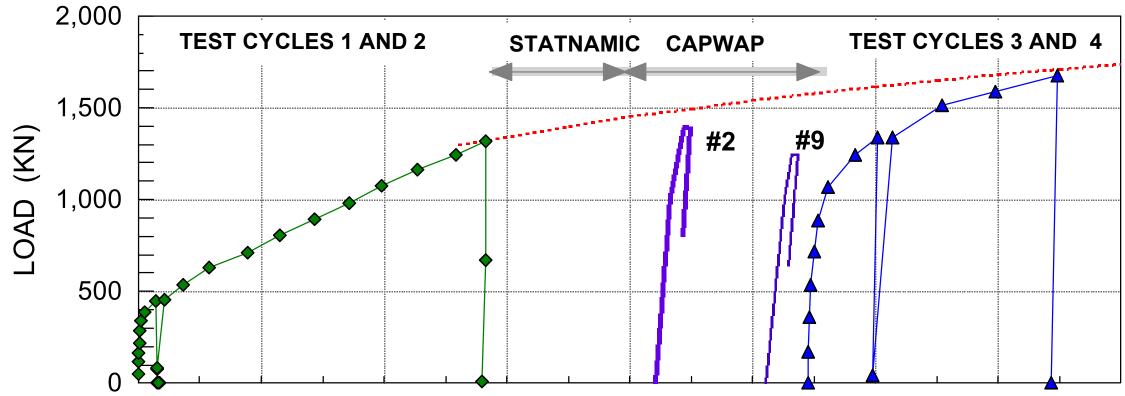

STATIC CAPACITY PREDICTION BY DYNAMIC METHODS FOR THREE BORED PILES[a]

Discussion by
Bengt H. Fellenius,[4] Member, ASCE

The authors have presented a well-documented case history with interesting conclusions. The discusser feels, however, that the analysis of the data could be pursued in an alternative manner, resulting in conclusions that both differ from and emphasize those of the authors.

Pile 2 was subjected to two series of static loading tests, called Tests 1 and 2, with intermediate testing using the Statnamic testing method and pile driving tests monitored with the pile driving analyzer. The pile driving tests involved a dozen impacts with an 85 kN weight used with heights-of-fall of up to 2.4 m, generating driving stresses in compression and tension of up to 15 MPa and 6 MPa, respectively. The concrete cylinder 28-day strength was 26 MPa and the pile was unreinforced. A CAPWAP analysis was performed on the records of the second and ninth blow.

The Pile 2 head movements measured for Test 1, the intermediate tests, and Test 2 were 140 mm, about 130 mm, and 100 mm, respectively, giving a total movement of about 370 mm. Both Tests 1 and Test 2 included an unloading/reloading event, separating each test on two cycles. The authors interpret the load-movements of the static tests plotted in Fig. 5 as two values of pile capacity, 1,068 kN in Test 1 and 1,602 kN in Test 2, according to their preferred "failure" criterion that the capacity is the load at a pile head movement of 10% of the pile diameter measured from the start of the test. However, Fig. 5 uses a common origin for Tests 1 and 2, which provides the misleading impression that Test 2 is independent of Test 1 and that its interpretation is unrelated to the load-movement

[a]July 2000, Vol. 126, No. 7, by Jean-Louis Briaud, Marc Ballouz, and Geroge Nasr (Paper 17460).

[4]Urkkada Technology, Ltd, 1010 Polytek St., Unit 6, Ottawa, ON, Canada K1J 9H8.

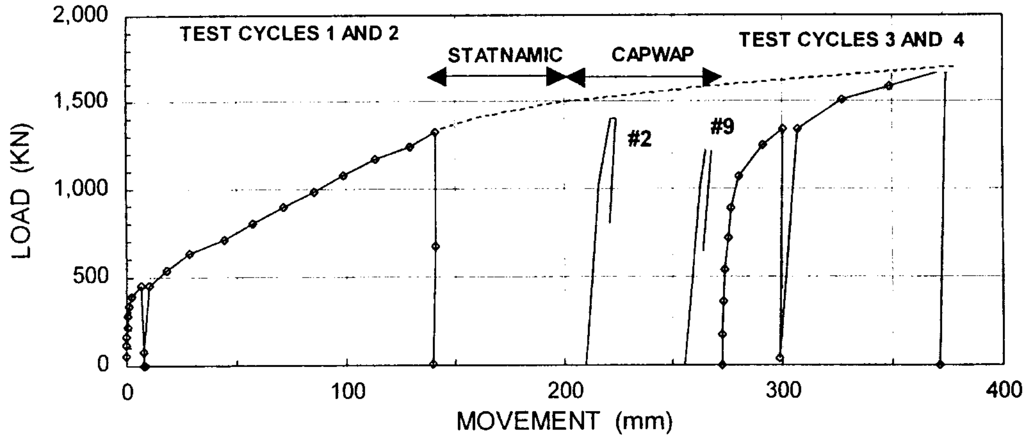

FIG. 16. Pile 2, Cycles 1 and 2—Sand Site: Load-Movement History

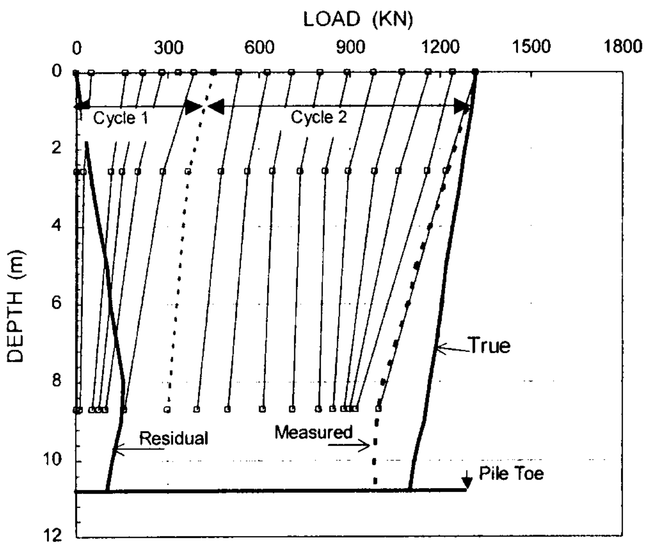

FIG. 17. Pile 2, Cycles 1 and 2—Sand Site: Load Resistance Distributions, Measured and Corrected for Residual Load

history. In contrast, the second cycles of Tests 1 and 2 are plotted starting from the point of net movement after the completion of the first cycle, maintaining the continuity of the test. The discusser prefers to consider the pile behavior as plotted in Fig. 16 (similar to Fig. 15), which maintains the test continuity from the start of Cycle 1 until the end of Cycle 4 with a "gap" due to the movements introduced by the intermediate testing.

Fig. 16 includes the load-movements of the CAPWAP-simulated static loading tests of Blows 2 and 9. The CAPWAP analysis for Blow 2, height-of-fall of 1.8 m, determined the pile capacity to 1,400 kN and shows that the impact resulted in maximum toe movement of 13 mm [pile compression was about 0.1 mm, only (G. Likins, Pile Dynamic, Inc., personal communication)]. This movement is not quite enough to fully mobilize the capacity of the 0.92-m-diameter pile. The Blow 2 CAPWAP curve, therefore, shows a slight underprediction of the pile capacity, but one that compares well with the test load of about 1,500 kN at its location in the load-movement history.

Blow 9, height-of-fall of 0.9 m, given to the pile when the previous blows had moved the pile about an additional 50 mm, resulted in a smaller toe movement and a correspondingly smaller CAPWAP-determined mobilized capacity, 1,250 kN.

The Fig. 16 load-movement diagram demonstrates the futility of comparing just the numerical capacity values determined from one or other definition of the static tests with the capacity values determined in the CAPWAP analyses without due consideration to the load-movement history.

The authors' comments on the residual load in the piles is very brief. In the discusser's experience, residual load will always develop in a pile, be it a driven or a bored pile. The distribution and magnitude will vary, of course. Usually, the small downward soil movement always occurring after the construction of a pile will induce load along the upper length of the pile. These loads will result in a small downward movement of the pile that is resisted by the soil in the lower portion of the pile. Because fully developed shaft resistance requires very small movement, the negative-direction shear forces along the upper portion and the positive-direction shear forces along the lower portion of the pile near the pile toe can be considered to be fully mobilized. A transition zone of some length between negative and positive direction forces exists along the middle portion of the pile. In contrast to driven piles, bored piles frequently exhibit only a small residual ("locked-in") toe load.

In a loading test, the negative-direction soil forces along the upper pile length are first overcome and then changed into positive-direction forces. This means that the loads measured along the upper length of the pile will indicate a shaft resistance that is exactly twice the true shaft resistance in this upper zone. The true resistance distribution is therefore a curve that is twice as steep as the measured curve. (It is beyond the scope of this discussion to give proof for why the magnitude of shaft resistance is independent of direction of movement.) Provided that the soil is reasonably homogeneous, the ultimate positive shaft resistance in and below the depth of the transition zone can be assumed to be similar to that along the upper length, and possibly all the way to the toe of the pile. The difference between the so-determined true resistance distribution and the measured resistance distribution is the distribution of the residual load in the pile. If the residual load in the lower portion of the pile (positive direction forces) is fully mobilized, the true distribution and the residual distribution are parallel, and, if not, the slope of the true distribution can never be steeper than the slope of the distribution of residual load along this length of the pile (because the positive shaft resistance cannot be smaller than the shaft resistance accumulating to the residual load).

The discusser has applied this analysis approach to the authors' test data for Pile 2 (obtained by digitizing the diagrams of the original FHWA report, Baker et al. 1993). The approach, presented in Fig. 17, uses the measured load distribution to determine the true resistance distribution (for the maximum load applied to the pile head), which is obtained after compensation for the residual load in the pile (the far-right curve).

The solid curve to the left is the calculated distribution of residual load. The dashed curve shows the resistance that would appear in load cells/gauges that did not consider the residual load in the pile (gauges zeroed at the start of the test). The three curves are interdependent and the analysis is based on establishing agreement between the calculated and measured loads.

The analysis results in the conclusion that the shaft resistance is slightly larger near the pile toe than near the ground surface, although not in proportion to the effective overburden stress. The resistance distribution shown corresponds to a unit shaft resistance of about 6 kPa and a total shaft resistance of about 200 kN (the variation of cross section reported by the authors has been considered in the analysis). At the maximum resistance, the mobilized pile toe resistance is about 1,100 kN corresponding to 1,670 kPa. The values are low and reflect the fact that the construction of Pile 2 was intentionally "messed up." The calculated residual toe load is small, about 100 kN.

The dynamic testing that was performed after the completion of the first static loading test on Pile 2 has most certainly affected both the zero values and calibration of the gauges as based on an intact pile cross section. The CAPWAP analysis of Blow 9 reports cracks in the pile, and it is more than probable that the driving compression stress of 60% of the 28-day strength coupled with the 6 MPa tension have damaged the pile. While the strain gauges in the pile still provide data, their calibration is lost and they cannot be used for determining the load in the pile. Fig. 18 shows the distribution determined from rejecting the strain gauge values and assuming that the pile shaft resistance is the same for Cycles 1 and 2 and Cycles 3 and 4. (There is no logical reason for why they would be different.) Using this approach in the analysis results in a maximum toe resistance of 1,270 kN (for the maximum applied load). The increase of 170 kN over the Cycle 2 toe resistance is due to the fact that the intermediate tests have compressed the soft soil below the pile toe by about 200 mm beyond the compression of Cycle 2. The results also indicate the residual toe load, the locked-in load prior to Cycle 4, to be about 200 kN.

The discusser has applied the analysis approach also to the results of the static loading tests on Piles 4 and 7, the well-constructed piles in sand and clay, respectively. Fig. 19 shows the results for Pile 4. The true resistance distribution diagram

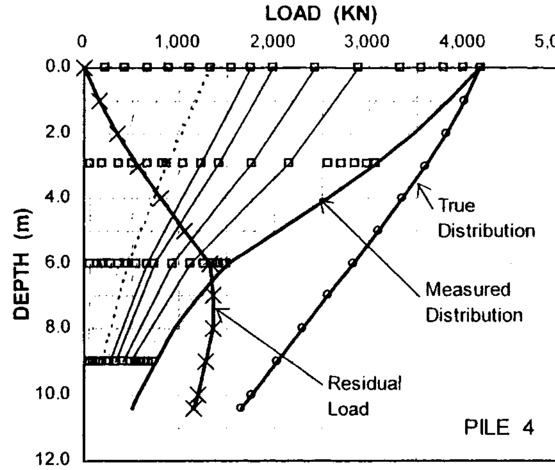

FIG. 19. Pile 4—Sand Site: Load and Resistance Distributions, Measured and Corrected for Residual Load

is the result of curve-fitting with recognition that the change of unit shaft resistance must be gradual (linear change was imposed) and that the results must show a resistance distribution agreeing with the loads measured in the pile for the maximum load applied to the pile head. The results indicate a maximum toe resistance of 1,650 kN and a residual toe load of 1,150 kN. The total shaft resistance is 2,500 kN (with the "bulging of the pile" accounted for), and the resistance distribution corresponds to a unit shaft resistance of 60 kPa at the ground surface and 90 kPa near the pile toe. The distribution also corresponds to a constant unit shaft resistance of 50 kPa coupled with a Bjerrum-Burland beta-coefficient of 0.25 per the classic Coulomb relation.

The results from the analysis of the measurements on Pile 7, the pile at the clay site, are presented in Fig. 20. The authors did not comment on the seemingly odd resistance distribution: the load values measured at 4 m depth are about equal to those at 8 m. That is, no shaft resistance appears to exist below the depth of 4 m. There is nothing odd about the values, however. They are typical of a pile subjected to residual loads. The discusser's analysis establishing the true resistance distribution indicates a total shaft resistance of about 1,900 kN, corresponding to unit shaft resistance values of about 60 kPa at the ground surface increasing linearly to about 80 kPa near the pile toe. The values can be compared to the undrained shear

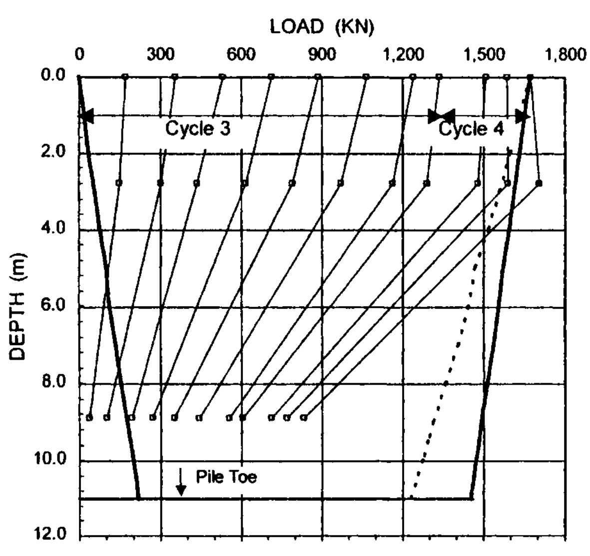

FIG. 18. Pile 2, Cycles 3 and 4—Sand Site: Load and Resistance Distributions, Measured and Corrected for Residual Load

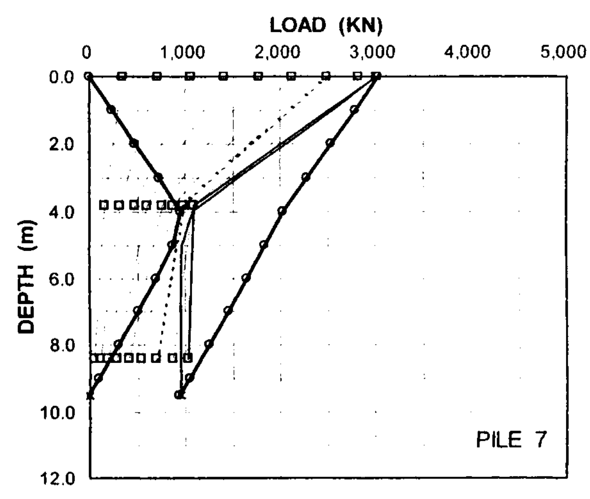

FIG. 20. Pile 7—Clay Site: Load and Resistance Distributions, Measured, Residual, and Corrected for Residual Load

TABLE 5. Shaft Resistance and Residual Loads—Comparison

Pile	Discusser		Authors	
	Shaft resistance	Residual toe load	Shaft resistance	Residual toe load
Pile 2, Sand site Cycle 2	200	100	175	180
Pile 2, Sand site Cycle 4	200	200	830	No indication
Pile 4 Sand site	2,500	1,150	3,300	No indication
Pile 7 Clay site	1,900	≈0	1,985	No indication

strength of the soil shown in Table 1 to be 110 kPa near the ground surface and 160 kPa near the pile toe. (Because the upper gauge in the pile appears to have failed to register the last load increment, the analysis is performed for the next to last load applied to the pile). These shaft resistance values are similar to those determined for Pile 4. The maximum toe resistance is nearly 1,000 kN. No (or only very little) residual toe resistance is discernable by the analysis; however, a considerable residual load in the pile still develops along the pile shaft.

The values of shaft resistance and residual load determined by the discusser's analysis are compared with those of the authors in Table 5.

The compilation table shows that where the discusser's analysis indicates residual load, the results of the test data differ between the discusser and the authors. In contrast, the analysis results agree for Pile 7, for which the discusser found no residual toe load.

The discusser agrees with the author that a lack of care, such as was *intentionally* was the case for Pile 2, can drastically impair the behavior of a bored pile. However, the movement required to mobilize the toe resistance was for all three piles rather large, about 50 mm, and it is questionable whether that large value, or for that matter 10% of the diameter (90 mm), can be useful as a reference to capacity or value to which to apply a factor-of-safety. The toe resistances mobilized at the Offset limit values were 300, 400, and 600 kN for Piles 2 (Cycle 2), 4, and 7, respectively, indicating no significant difference between the "messed up" pile and the other two piles.

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