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DISCUSSIONS AND CLOSURES

Discussion of "Load Testing of a Closed-End Pipe Pile Driven in Multilayered Soil" by D. Kim, A.V.D. Bica, R. Salgado, M. Prezzi, and W. Lee.

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The authors have presented a case history on the results of a static loading test on a strain gage instrumented, 356 mm diameter, closed-toe, pipe pile, driven 17.4 m into a clayey silty soil with layers of sand. It is appreciated that the paper includes comprehensive background information on the soil profile, installation data, as well as the results of the static loading test. The paper presents the dynamic (driving) data, pile-head load-movement, residual load, shaft and toe resistances, and total capacity. This information is useful for piled foundation design in the general area and geology of the test site. However, in my opinion, the test results would be useful also for a wider application, if the authors could provide more of the basic results data, and if the paper had included a more detailed analysis. Specifically, a table showing the applied loads and the end-of-increment duration strain-gage determined loads. It would also be of value to show the full diagram from the cone sounding at the test pile location (cone stress, sleeve friction, pore pressure, and friction ratio). With regard to the analysis, I believe users of the paper would appreciate a diagram showing the results of analysis of the cone penetrometer sounding at the test pile location in terms of distribution of shaft resistance for the different methods used, which would be more informative than the brief listing in Table 5 (in original paper) of the total capacities obtained from such calculations. Moreover, I find it disappointing that the authors have not provided a reference to an effective stress calculation with the main reference value being the effective stress ratio, the so-called beta-coefficient, which, in my opinion, is the most basic correlation of the results of a static loading test and most suitable also as correlation to shaft resistance in clay.

The authors indicate that the pile capacity in the first static loading test is 1,500 KN, which is close to the 1,512 KN load applied to the pile head in the fifth increment of the seven increments of load reported in the paper. The shaft resistance, determined as the difference between the applied load and the toe resistance shown in the load distribution curves (Figure 8a of original paper), is very similar for Increments 4 through 6. Moreover, the shaft resistance mobilized for Increment 7, i.e., when the pile experienced plunging failure, is also quite similar to that of the preceding three increments. As shown in Figure D1, the difference is mostly in the lowest 1.5 m length of the pile. Indeed that similarity, the comparable magnitude of shaft resistance determined in the second loading test, and the fact that the second loading test indicates the same ultimate shaft resistance (albeit a stiffer response), as the first test indicates that the soil is neither strain hardening nor strain softening.

By fitting the shaft resistance to an effective stress distribution, I have estimated a distribution of the beta coefficients that produces a shaft resistance distribution that is equal to the measured distribution. I have assumed that the pore pressures are hydrostatically distributed below the groundwater table (located 1.0 m below the ground surface). The results are presented in Figure D2. Beta coefficients of 0.6 and 1.4 are high for the silty sandy soil layers at the site, having compressibility values (Table 1 of original paper) that correlate to virgin Janbu modulus numbers ranging from 2 to 4 and recompression modulus numbers ranging from 11 to 37. These values are representative for a highly compressible soil. It is my experience that, when driving displacement piles into such soils, the subsequent reconsolidation, and set up process will give rise to significant residual loads in the pile as well as a residual-load force equilibrium located close to the pile toe. The authors mention analysis of residual load, but state it to be minimal when compared to the "measured capacity". They, therefore, disregard its influence on the results of the test.

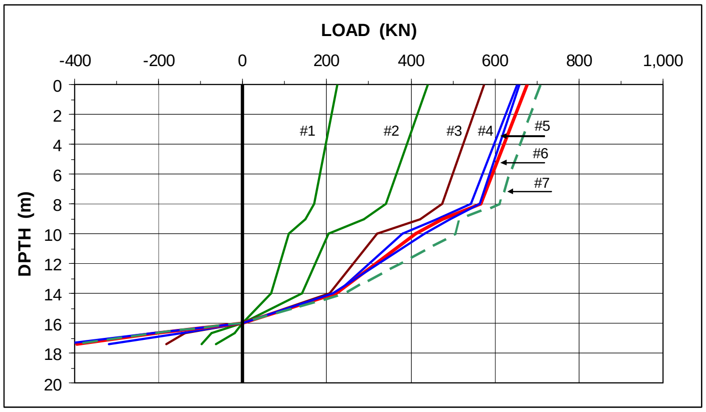

Fig. D1. Distribution of shaft resistance, set to zero at 16 m depth.

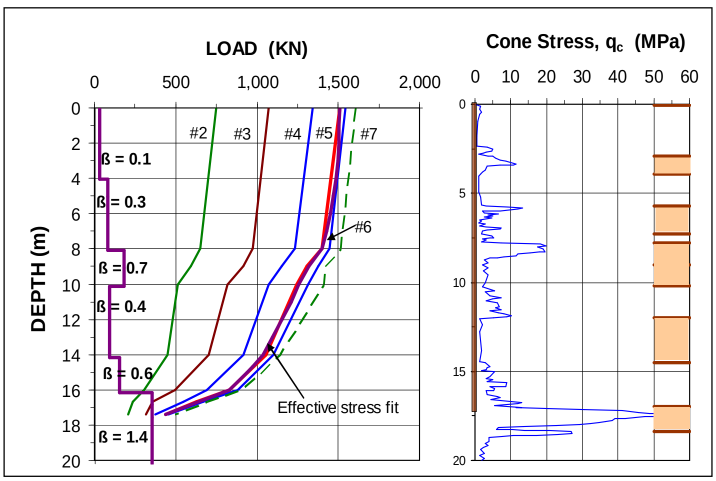

Fig. D2. Distribution of measured resistance, resistance fitted to that of Increment 5, and the ß-coefficients used to achieve the fit. The cone stress diagram and a delineation eleven soil layers are added for reference.

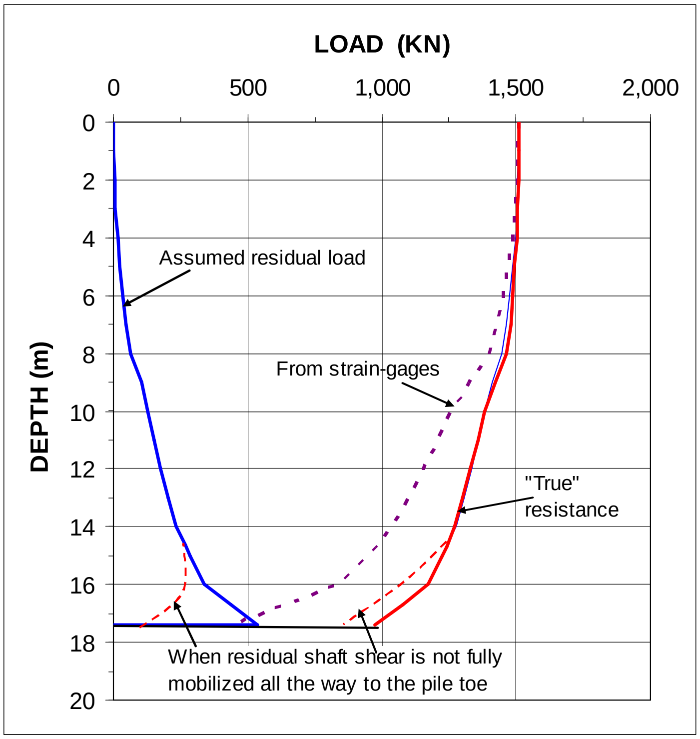

Fig. D3. Distribution of measured resistance from strain gages directly, residual load assumed fully mobilized, and "true" resistance

The authors compare the residual load to the pile capacity and indicate that the ratio between the maximum residual load — reasonably estimated — and the pile capacity is about 1 over 6, which is not a large number. However, correlating residual load to the pile capacity is not meaningful, but including it is essential when determining pile shaft and toe resistances is (Fellenius 2000, 2002a, 2002b, 2009). In a compressible, soil such as at this site, it is most likely that the residual load is built up by fully mobilized shaft shear. For this condition, the residual shaft shear along the pile must be in the negative direction more or less all the way to the pile toe. Figure D3 shows the distribution of residual load and the corrected load distribution, the "true" resistance distribution. The shaft resistance of the latter is half that measured, the toe resistance is about twice that measured, and the corrected beta coefficients are half those indicated in Figure D2. Were the residual shaft shear after all not fully mobilized near the pile toe, then, the residual load at the pile toe would be smaller and the residual-load force equilibrium lie correspondingly higher up in the pile, as indicated by the dashed curves in Figure D3. If so, the corresponding beta coefficient immediately above the pile toe would be about unity, which is representative for a very dense silt, but hardly so for a compressible clayey silt. A more exact determination of the residual load would require a direct measurement by, for example, performing an O cell test instead of the head-down test. Though the curves shown in Figure D3 may only be approximately close to actual "true" distribution curves, they yet demonstrate that residual load is not negligible in the analysis of the test results.

The authors report that the strain gage readings before the static loading test are questionable due to "drift" occurring during the driving. Alteration of gage readings due to construction is a recurring problem with any instrumented pile and is due to many effects, zero drift being one. Instrumentation of steel pile is usually completed above ground at a temperature that is different from that down in the soil, and strain gages, even if by themselves unaffected by temperature changes, will dutifully register the strain changes due to the change of temperature of the pile material. Moreover, for a steel pile, strain is built-in during the manufacturing process, and this can be partially released when the pile is driven. The pile-soil interaction during the driving and the difference between the shaft resistance (requiring only small movements to change values) and the toe resistance (requiring larger movements) mean that additional strain is built-in due to the driving. Once driven, the recovery of the soil from the driving disturbance will add to (or reduce) the strain already in the pile. It is not that the gages themselves drift — these days, the gages are quite reliable — rather, the pile construction process imposes strain, and significantly so. However, the problem is not the change per se, it is that the engineer performing the test needs to include this change in the analysis and to separate the change that is not caused by the soil or is affecting the soil from those which have, and that is very difficult as long as the measuring system uses the pile as a part of the gage. Normally, we have to work from the strain changes imposed by the test, as in the authors' case. However, this does not mean that one can assume zero strain and zero load in the pile at the start of the test. Conclusions drawn from the test results when the effect of residual load is neglected will be unconvincing.

The authors do not report the pile toe movement. However, the pile shortening is small in relation to the pile head movement, and the pile toe movement can be determined approximately from subtracting calculated pile shortening from the information on measured pile head movement for the applied load increments. Figure D4 shows the load-movement for the pile toe in the two tests calculated accordingly. The values are not corrected for residual load. At about 55 mm movement, the Test 1 curve implies a change of response that could be interpreted as a definition of an ultimate toe resistance. However, up to that point, the response is a re-loading of the pile toe. A potential virgin pile-toe response is indicated in the figure. In fact, of the three components of pile head movement measured in a static loading test, only the shaft resistance exhibits something that can be termed ultimate resistance, or "capacity". The second component is 'elastic' shortening of the pile, which is a smaller or larger portion of the total movement depending on the length of the pile and on whether or not the load generating the shortening has overcome the shaft resistance along the full length of the pile. The third is the pile-toe load-movement response, which in most cases is a curved line showing no ultimate resistance or failure (Fellenius 1999). Therefore, definitions of total pile capacity, as well as toe capacity, if meant to be ultimate values, are extraneous. Of course, the concept of total pile capacity has been in general use for almost a 100 years and is not going to go away. However, for the individual components, the term is only truly applicable to shaft resistance, when there is no definite strain hardening or strain softening response, which is the case for the subject test. (If the soil exhibits strain hardening, the term "ultimate resistance" does not apply. If strain softening, the term "ultimate resistance" applies only to the shaft resistance at a certain pile element, not to a single total shaft resistance value unless it is calculated from the individual elements). For the other two components, pile shortening and pile toe response, the concept of capacity has little relevance. As to the authors' reference to the capacity being the load that caused a movement equal to 10 % of the pile diameter, it a useless definition. This definition was first proposed by Terzaghi 60 years ago for the analysis of small footings and laboratory tests for lack of any more suitable definition. It is of absolutely no relevance to the analysis of a loading test on a pile, or for that matter, on a full size footing.

The authors comment on the fact that the two static loading tests performed at 50 days and 90 days after the driving show only a small increase of total capacity and no increase of shaft

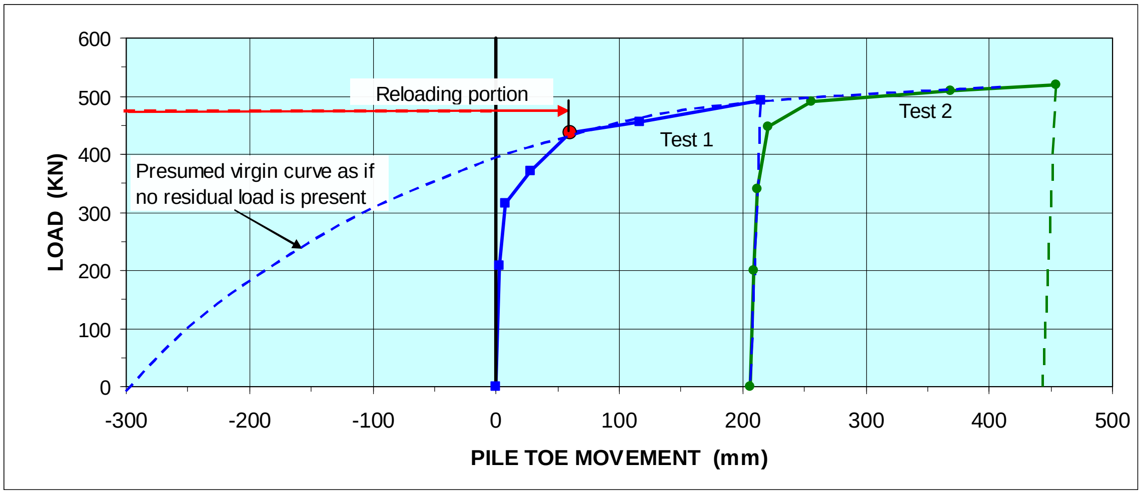

Fig. D4. Calculated pile toe load movements: Test 1 and Test 2

resistance, in contrast to the increase shown by the CAPWAP analyses of the restrike blows for the two other pipe piles driven at the site. However, the data do not necessarily conflict. I have plotted the values in Figure D5, which shows that, first, for each restrike event, the pile response stiffer for the subsequent event. This does not necessarily include an increase in shaft resistance, For each restrike, the pile is driven a bit deeper into the dense material at the pile toe, generating a larger toe resistance, and therefore, a larger pile capacity (as also is implied in Figure D4). As indicated in Figure D5, in contrast to what is reported from the dynamic tests, the change in shaft resistance observed in the static tests is moderate, only.

The authors do not report the number of restrike blows given and the total penetration for each event. As indicated by the pile driving diagram (Figure 4a), it does not take much additional penetration for the pile toe resistance to increase considerably. Moreover, as for the static test, presence of residual load will cause a dynamic analysis (CAPWAP) to indicate a larger than true shaft resistance and a correspondingly smaller toe resistance (Fellenius 2004). It may well be that the shaft resistance values for the restrikes are overestimated and the toe resistance values underestimated. Probably, therefore, but still only hypothetical, after the first about 30 days, as for the test piles, the shaft resistance was approximately unchanged, but the toe resistance increased due to the repeated driving.

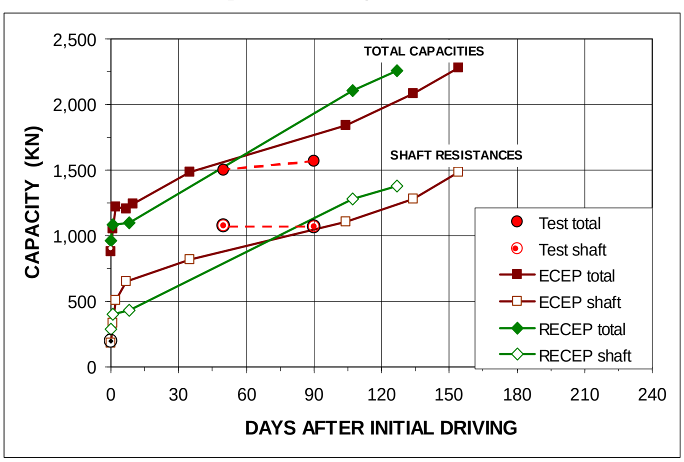

Fig. D5. Values of shaft resistance and total capacity from static loading tests and from CAPWAP analyses versus days after initial driving plotted from Table 3 in the original paper.

I disagree with the authors' conclusion that axial response of a single pile is not well understood. It is in fact rather well understood, and if the pile is driven or otherwise constructed or the soil is uniform or multilayered makes little difference. That is, the principles and the qualitative response are understood. Obtaining quantitative values is a different matter, however, and this is what the authors might have meant. To enable the profession to calculate the actual values, that is, to design piled foundations, requires reference to results of well-instrumented tests analyzed test, similar to the test and paper presented by the authors. The authors' effort to write up this project-related study into a full journal paper is appreciated.

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No closure with additional data was offered for this discussion