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The response of a "plug" in an open-toe pipe pile

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ABSTRACT: Two published case histories are taken as reference to a discussion on how to consider the effect of soil core inside a pipe pile driven open-toe, as opposed to the response of a pile driven closed-toe. The analysis of the measurements shows that the comparison has to be made in terms of deformation, not capacity. Both piles have similar shaft resistance along the outside of the pipe. For the closed-toe pile, toe resistance acts along the full cross section. For the open-toe pile with a soft core, some toe resistance is mobilized by the force against the steel annulus. The soil force that acts at the bottom of the core, pushes the core upward much like the upper portion of a pile tested in a bidirectional test and the upward movement is resisted by shaft resistance along the inside of the pile. However, the core is very soft compared to a pile and the movement of the pile toe is quickly spent, resulting in a limited magnitude of inside shaft resistance, moreover one acting only along a limit length of the pile up from the pile toe. Recommendations for how to analyze the response of an open-toe pile are presented and a comparison is provided between the results of a simulated static loading test on a closed-toe and an open-toe pipe pile are presented, showing that the comparison—and piled foundation design—have to recognize and consider the pile toe movement during service conditions.

KEYWORDS: closed-toe and open toe pipe piles, soil core response, effective stress analysis, t-z and q-z functions, load-deformation considerations, influence of residual load.

INTRODUCTION

A frequently asked question is what is the effect on the response to load of a pipe-pile driven open-toe with an inside soil column as opposed to the same pile driven closed-toe. Of course, the immediate comment is that the closed-toe pipe might not have reached the same depth as that of the pile driven open-toe. But, if we assume that they yet are at the same depth, then what? We relate the response of an open-toe pipe pile to that of a closed-toe pipe pile, not because we have the alternative of using a closed-toe pile, but because we believe we understand the response of the closed-toe pile and want to relate the different response, as we expect it to be, of the pile with the inside column to the known response. Actually, the most common question asked is more specific: here is a pipe pile with a column of soil inside and how does the pile support a structure? Does the inside soil column, the core, act as a plug or does the pile slide down over it? And, does the core contribute to carrying the load? Much of the reason for the conundrum lies in the insistence of the profession to think in terms of capacity as opposed to deformation, movement, and settlement. As will be presented in the following, when the analysis is made in terms of deformation, the response of a pile to load, whether the pile is a closed-toe pipe, or a partially or fully plugged pipe can be addressed by the same analytical approach.

DISTRIBUTION OF FORCES IN AN OPEN-TOE PIPE PILE AS OPPOSED TO A CLOSED-TOE PIPE PILE

When driving an open-toe pipe pile, sometimes, a short, almost rigid plug is formed early in the process. If so, in the continued driving, the pile responds much like a pipe driven closed-toe. This is a special case. While some concern might be expressed as to the integrity of that plug in the long-term service conditions, it will not be discussed in this paper. Instead, this paper addresses when the open-toe pipe has cored the soil and at the end of the driving, a significantly long soil column—a core—exists inside the pipe.

The coring and plugging during the driving has been addressed by several researchers, e.g., Paikowsky et al. (1989), Paikowsky and Whitman (1990), Raines et al. (1992), and Paik et al. (2003), and, more recently, Jeong et al. (2014). Most depict the forces acting on the pipe pile during driving as shown in Figure 1A, i.e., as shear forces acting both along the outside and the inside of the pipe; full length of the pile. The force-arrows indicate that the pipe would be subjected to resisting soil force both at the bottom of the core and along the inside of the shaft, but the response cannot be both, it must be one or the other. That is, if the pile experiences a toe resistance, it is plugged and there is no inside shaft shear (but for along a short plug length). As shown in Figure 1B, if on the other hand the core can move, then, there is an inside shaft shear (along the core). The pile does not experience toe resistance (but for the annulus area, the relatively small area of the steel pipe wall), only inside shaft resistance. Of course, the core experiences a "base" force, in balance with its shaft resistance ("the inside shaft resistance"). Note, the inside shaft resistance is only mobilized along the length necessary to match the imposed toe movement.

In the driving of the open-toe pipe, the core would be affected by some shaft resistance also along its upper length, which would develop due to the inertia of the core mass. In static loading, that inertia resistance does not develop, however, and, for the open-toe pile, the static response is as depicted in Figure 1B.

Figure 1C shows the forces acting on the core as a response to static loading of the open-toe pipe pile. The sketch indicates that the force at the bottom of the core has only been able to have an influence on a certain distance up the core. This is because the core compresses in response to the soil force resisting the downward movement, which causes a relative movement between the core and the inside of the shaft, which, in turn, is the cause of shear forces as illustrated by the arrows. No leap of imagination is needed to realize that the core can be considered to be a pile turned upside down, or, perhaps, as the upward portion of a pile tested in a bidirectional test.

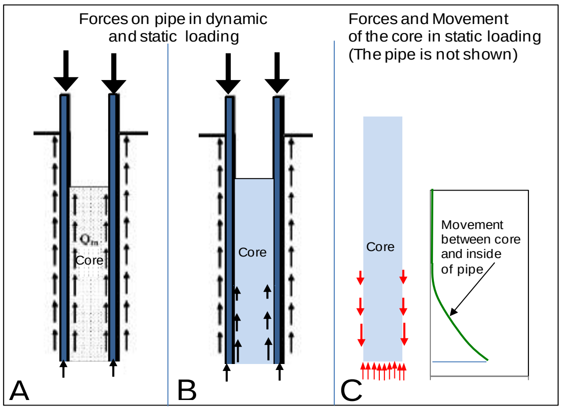

Fig. 1 Advancing an open-toe pipe pile. **A**. dynamic loading; the entire length of core is engaged (only showing forces acting on the pipe). **B**. static loading; only the lower length of core is engaged (only showing forces acting on the pipe). **C**. static loading (only showing forces acting on the core).

The key point to realize is that such a core-pile is soft in relation to the usual pile. Its axial deformation modulus, E, is about equal to that of soil, albeit compressed under confined condition.

The stiffness of the core is, therefore, about 3 to 4 order-of-magnitudes smaller than that of a pile of the same diameter. Moreover, as indicated by O'Neill and Raines (1991), the effective stress in the core is constant (uniform material is assumed). Therefore, the unit shear resistance between the core and the inside of the pipe is more or less constant and modeling the shear force distribution along the core should be by means of average shear force; by total stress analysis so to speak. The shaft resistance along the outer pipe, of course, must be modeled using effective stress principles.

If we now imagine the core as a soft pile pushed upward a distance equal to that of the pile toe movement in a static loading test, with the toe force compressing the core, we can appreciate that the imposed movement can never result in a large force at the bottom of the soft core and that the base force will have been "spent" within a short distance up from the core bottom. Although, the force-movement response of the core—unit shear resistance along the inside of the pipe—is more or less an elastic-plastic response, combined with the gradual mobilization of the core length, the response is similar to the usual pile toe response, i.e., an almost linear or relatively gently curving, force-movement of a pile toe. The difference in response between the two curves is due to their different stiffness, i.e., their difference in slope.

TWO CASE HISTORIES

Case by Paik et al. (2003)

Paik et al. (2003) presented a study on a strain-gage instrumented, double-wall pipe pile, driven to 7.0 m depth into a compact gravely sand containing no fines and subjected to a static loading test. The groundwater table was located at 3.0 m depth. The pile was built up combining two pipes and consisted of an outer pipe and an inner pipe with a small annulus void containing spacers to prevent the two pipes from interfering with each other. They were constructed from an outer, 356 mm OD, 6 mm wall pipe and an inner, 292 mm OD, 6 mm wall pipe. The pile had a stick-up above ground of 1.2 m, which allowed a strain-gage pair to be placed level with the ground surface to measure for each pipe its portion of the applied load.

Figure 2A shows the forces measured along the outer pipe. (The gages along the lower length of the outer pipe did not survive the driving). The force distributions show the effect of reducing force due to shaft resistance and, as the dashed extrapolation would suggest, a very small toe resistance, commensurable with the pipe wall acting on the soil at the pile toe.

Figure 2B shows the forces measured along the inner pile. The most interesting observation is that no change of load in the pile occurred above 5 m depth, that is, the soil resistance acting along the within the lower 2.0 m length of the core was sufficient to resist the soil force at the core base. The slope of the distribution line from the pile toe to the 5 m gage increased with increasing load, which indicates that the shaft resistance between the core and the inside of the inner pipe progressively acted along a longer length of the core. Moreover, in contrast to the outer pipe, a significant force is implied for the inner-pipe bottom end.

Case by Jeong et al. (2014)

Jeong et al. (2014) tested three double-wall, instrumented pipe piles fabricated in a similar manner as used by Paik et al. (2003). Here, only the results from Pile 2 of these tests will be presented. The two pipes were constructed from an outer, 711 mm OD, 7 mm wall pipe and an inner, 610 mm OD, 9 mm pipe. The test pile was driven to 11.4 m depth into a hydraulic sand fill of a relative density at the boundary between loose and compact state. The groundwater table was located at 2.5 m depth. At the pile toe, the annulus between the pipes was closed by welding the pipes together (Paik et al. (2003) used a silicone seal to seal off the annulus).

Because pipes were forced to stay equal in length, when load was applied to the upper ends of the pipes, the lower end of the outer pipe was pulled by the inner pipe, and the latter was correspondingly pushed by the outer pipe. The records would have been more representative for a pipe with an inside soil column had the inner pipe been designed shorter than the outside pipe (free end at the pile head), or, of course, had the seal been made without the physical connection between the lower ends of the pipes.

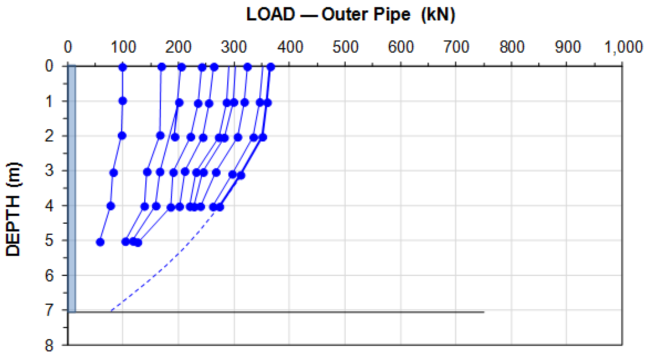

Fig. 2A Force distribution in the outer pipe
(data from Paik et al. 2003)

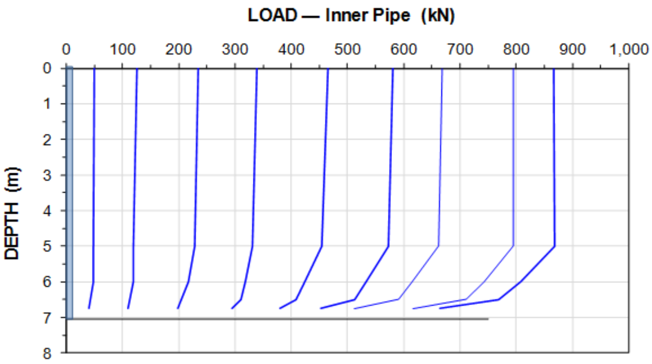

Fig. 2B Force distribution in the inner pipe
(data from Paik et al. 2003)

Figure 3A shows the forces measured along the outer pipe of Pile 2. The first gage reading was from 1.9 m depth. The negative load values measured in the outer pipe at the gage level placed 0.3 m above the pipe end are a consequence of the rigid connection between the two pipes at the pile toe.

Figure 3B shows the forces measured along the inner pile. The first gage reading was from 3.7 m depth. Similar to the Paik et al. (2003) case, shaft resistance between the core and the inside pipe only developed along the lower 2-m length of the pipe. Again, the slope of the distribution curve between the lowest gage (at 11.1 m depth and the gage 2 m above (9.1 m depth) increased from one load to the next, indicating that a progressively longer length of the core became activated during the loading test. The significant resistance at the bottom end gage level is an effect of the welded connection between the two pipes.

The load-movement records of the static loading tests were not included in Jeong et al. (2014), but are available in a presentation by Ko and Jeong (2015). I have plotted these records in Figure 4 along with the load-movement records for the outer and inner records obtained by combining the pile head movements with the strain-gage determined loads for the outer and inner pipes in Figures 3A and 3B as measured at depths of 1.9 m and 3.7 m, respectively.

In Figure 4, the sum of the outer and inner pipes should be about equal to the applied load ("Head both pipes"), but they are not. As can be expected from the response of the inner pipe (Figure 3B), no change of resistance is likely to have developed between the pile head and the first gage level (3.7 m depth). In contrast, between the pile head and the first gage level in the outer pipe, an extrapolation indicates that up to 80 kN might have developed as shaft resistance along the outer pipe before the 1.9-m depth. I believe the indicated about 400-kN difference between the sum of the outer and inner records of load and the 2,000-kN applied load is due to the interaction between the two pipes.

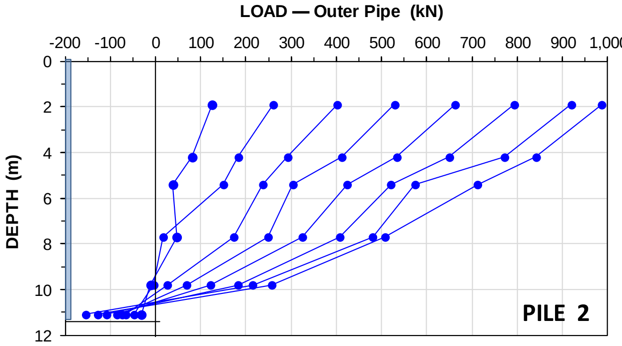

Fig. 3A Force distribution in the outer pipe (data from Jeong et al. 2014)

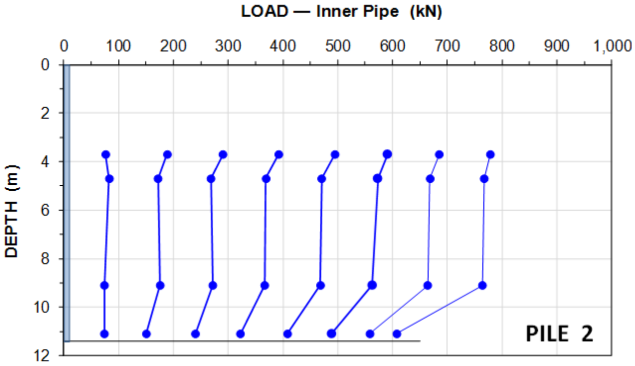

Fig. 3B Force distribution in the inner pipe (data from Jeong et al. 2014)

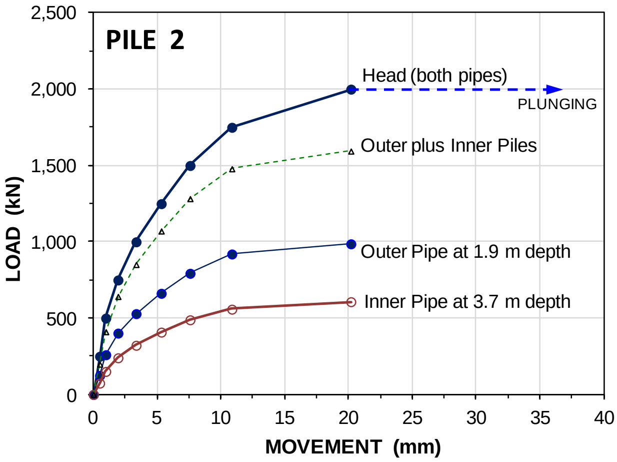

Fig. 4 Load-movement curves for pile head and for gage depths at 3.7 m and 1.9 m for outer and inner pipes, respectively

Figure 5 shows the difference in load-movement between the inner pipe 9.1- and 11.1-m gage depths. The curve represents the shaft resistance along the inside of the core mobilized in the static loading test as the inner pipe was pushed down. I will address the dashed line labeled "Simulation" later.

DISCUSSION

To some extent, the following discussion applies to both case histories. However, only the second case is addressed specifically.

For the second case history, I assumed that the shaft resistance of the outer pipe is about 800 kN at a 20-mm pile head movement. The value includes the estimated resistance above the 1.9 m gage depth. An effective stress back-analysis for this shaft resistance along the full length of the outer pipe correlates to an average beta-coefficient equal to about 0.40, which is a realistic value for sand.

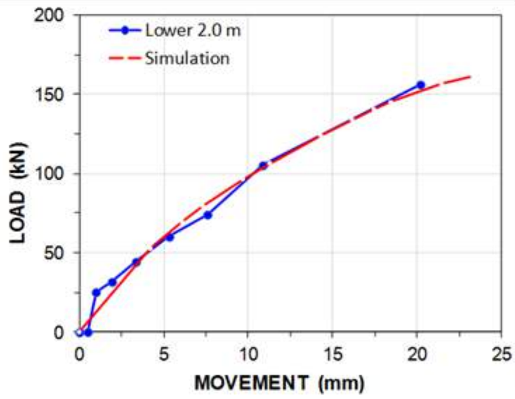

Fig. 5 Load-movement for inner pipe shaft resistance measured between 9.1 m and 11.1 m depths

At the 2,000-kN maximum load applied, the remaining load, about 1,200 kN, would be toe resistance that would correlate to a 3 MPa stress over the full cross section of the outer pipe (3,970 cm^2)—as if the pile would have been a closed-toe pipe pile. The 3-MPa value is somewhat large for a loose to compact sand, but the driving might well have densified the soil around and below the pile toe.

A detailed back-calculation fitting the measured distribution for the outer pipe would indicate a beta-coefficient larger than the 0.40 average value along the upper 4 m length, which would be commensurate with the measured forces being influenced by residual load. However, if the build-up of residual load would extend all the way to the pile toe, an analysis to fit to the records would have to assume a large residual compressive toe load and the measured toe force be very small, but the records would also indicate a very small unit shaft resistance (small beta-coefficient) near the pile toe. No such small ß-values appear. Therefore, I conclude that if any residual toe resistance has affected the force measurements in the outer pipe, it was too small to have had any significant effect.

The inner pipe does not have outside contact with soil, so no residual load can have developed along the outside of the inner pipe. There might have been residual forces distributed along the core, inside the inner pipe, however. Near the top of the core, they would be manifested as negative directed shear force and near the bottom of the core, as positive directed shear force. If so, the measured forces in the pipe, where positive direction residual forces exist, will be smaller than the true force. It must be realized, however, that the residual shear force can only affect the measurement if there is movement between the pipe and the core. Therefore, as no change of load developed above the 9-m depth, no relative movement and force changes occurred in the core above the lower 2-m length. The effect of residual force along the core would be that the forces measured in the lower 2.0-m length would be correspondingly smaller than the true forces.

The about 400 kN (600 - 200 kN) implied toe resistance shown in Figure 3B, calculated as acting on the steel areas of both pipes together plus the area of the annulus between the pipes, which was welded closed (total 1,220 cm^2), corresponds to a stress of about 3.2 MPa, which is somewhat larger than that expected in a loose to compact sand. In contrast, the about 150 kN total shaft resistance mobilized along the core at the 20 mm pile toe movement corresponds to a core toe stress of 0.5 MPa., which is on the low side in a loose to compact sand for the measured movement. Possibly, the loads indicated for the inner pipe gages are underestimated due to presence of residual load along the core.

It is not the objective of the paper to pursue all details of the two case histories. Whether the force values measured in the inner pipe are true or larger than indicated, the two case histories show that the core responds to the downward movement along a length determined by the soil force and the mobilized core resistance as activated by the relative movement between the soft core and the in relation immensely stiffer steel pipe.

The measured response of the core can be modeled in a bidirectional test on a short pile with a very low stiffness. Taking the measurements as true, the 150 kN force at 20 mm movement corresponds to a 40 kPa unit shaft shear along the core over the 2-m distance between the two lower gage levels. For the imposed force to be spent at a movement of 20 mm, the core modulus, E, needs to be 40 MPa. This correlates to a Janbu modulus number of 400, which is representative for a sand having been compacted and confined. Would the test have been continued to larger toe penetration, a longer length of the core would have been engaged and, eventually, had there been a gage level at, say, 1 m further up the core, it would have registered a load change. The fit to the measured core response is indicated in the curve marked "Simulation" in Figure 5. It was produced using the UniPile software (Goudreault and Fellenius 2014) applying t-z functions and resistances to achieve the fit.

COMPARISON BETWEEN THE RESPONSE OF A CLOSED-TOE PILE AND AN OPEN-TOE PILE

The common approach to analyzing the effect of the core in an open-toe pipe pile, as opposed to that of a closed-toe pipe pile, is to resort to a capacity comparison. However, this approach will not address the real difference between the two pile types, as demonstrated by the two quoted case histories. The effect of a core inside the pile is that of a soft toe response. That the ultimate resistance, i.e., the response at large movement, is different between the closed- and open-toe pipes is not the key issue. Moreover, if a comparison is made for cases at different magnitudes of pile toe movements, obviously, no apple-to-apple correlation exists.

Figure 6A shows a simulation of a closed-toe pipe pile of dimensions similar to the outer pile of the second case history (OD 711 mm, wall 7 mm, and length 11m) driven into a sand similar to that of the case history. The simulation is made using the UniPile software (Goudreault and Fellenius 2014) using an average beta-coefficient of 0.40 and a toe resistance of 2 MPa.

The shaft response is described by a hyperbolic function with the 0.40 beta-coefficient shaft resistance occurring at a relative movement of 5 mm between the shaft and the soil. The toe resistance, 2 MPa, is described by a ratio function with an exponent of 0.600 and the 2-MPa value mobilized at 30-mm toe movement (Fellenius 2014).

Figure 6B shows the simulated load-movement curves for the pile driven open-toe assuming that after the driving, a soil core exists inside the full length of the pipe. The outer shaft resistance is the same as for the closed-toe case. Moreover, I have assumed that the shear force between the core and the pipe has been activated along a 2.5 m length, that the average shear force is 40 kPa, and that the core has an E-modulus of 50 MPa. This establishes that, for a toe movement of 30 mm, the toe force is about 200 kN. With a bit of allowance for the force on the steel wall (the 7-mm annulus of the pile; the steel cross section), this is the toe resistance of the open-toe pile at that toe movement.

While the shaft shear between the core and the pile is assumed to be almost elastic-plastic, the gradual increase of force against the core base is best described by gently rising ratio function, as established in an analysis of the core for the mentioned assumptions using the upward response of the core in a bidirectional test. This is indicated in the toe curve in Figure 6B.

Ultimate resistances for the pile head and pile shaft elements occur at different movements relative to the soil. Of course, an ultimate resistance can always be defined from the pile head load-movement curve by some definition or other. Whatever the definition, it has little relevance to the difference in response between the pile driven closed-toe as opposed to that driven open-toe. A useful relation is the load at the pile head that results in a certain pile toe movement.

Circles in Figures 6A and 6B indicate the pile head load for a 5-mm toe movement, which is usually a safe value that includes an allowance for downdrag and group factors that can increase the toe movement during long-term service, and, therefore, the pile foundation settlement. Note that although the difference in toe resistance at the large toe movement (30 mm) is about 600 kN, at the more moderate 5-mm toe movement, the difference is only 200 kN between the closed-toe and open-toe pile alternatives.

In back-calculating the results of an actual static loading test on an open-toe pipe pile with a soil core and modeling the forces measured in various locations along the pile, the core effect cannot be treated as an ultimate toe resistance, but needs to be considered as an add-on shaft resistance along a lower length of the core. This add-on shaft shear can be obtained by modeling the core effect separately assuming as if it is tested upward in a bidirectional test. While the core base (pile toe) movement is a measured value, the unit shaft shear along the core and the core stiffness will have to be assumed or determined in special tests.

Residual load distribution is rarely measured (it is rather difficult to do). However, its influence can be significant and a back-analysis would have to make allowance for this. The results are then best presented as upper and lower boundary solutions. However, it is beyond the scope of this paper to address this issue.

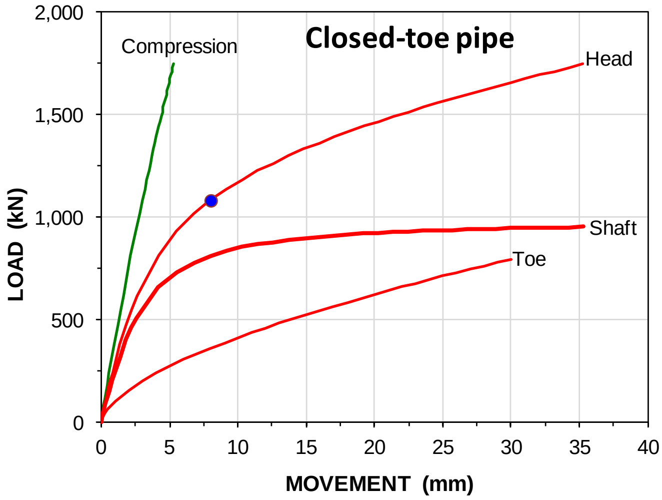

Fig. 6A Load-movement curves for a static loading test on the closed-toe pile. The solid circle indicates the pile head load that generated a 5-mm toe movement

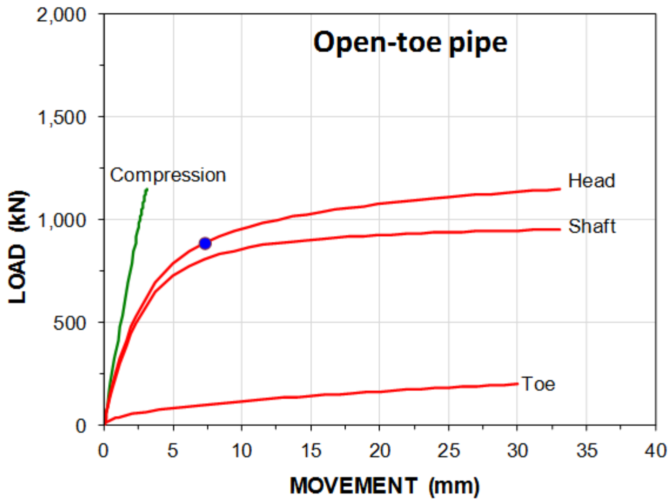

Fig. 6B Load-movement curves for a static loading test on the open-toe pile. The solid circle indicates the pile head load that generated a 5-mm toe movement

CONCLUSIONS

In analyzing the results of a static loading test on an open toe pipe pile in terms of capacity, the conundrum that the inside soil column is either acting as a rigid plug and, therefore, the pile would develop a toe resistance or, on the other hand, the inside soil column acts in supplying inside shaft resistance, but no toe resistance. However, both scenarios can be analyzed using the same model of response, provided that the problem is approached considering the deformations—load-movement response—and the fact that in a static loading test, as well as in service, the core inside a pipe pile driven open-toe acts as a soft pile pushed from below. There is in all cases a relation between the shear force acting along the core, the stiffness (EA) of the core and the resistance exerted by the downward pile-toe movement.

Trying to explain the difference between the response of a closed-toe and open-toe pipe pile by considering ultimate resistance—capacity—will not provide useful results.

In principle, the toe relation for the core is simple: the maximum toe core force at any given toe movement is governed by the unit shaft shear of the core along the inside of the pipe and the stiffness (EA) of the core. Considering the small pile toe movements, the force on the core and that, therefore, the inside shaft resistance will be small in relation to the outside shaft resistance and the toe force acting on the steel annulus.

It is important that the analysis of the pile response considers the effect of residual load in the pile.

The static tests on the double-wall pipe piles provided the important observation that the inside soil column is engaged from bottom up and only along a length corresponding to the spring compression necessary to counter the force on the core.

In contrast, the second case-history arrangement of connecting the outer and inner pipes at both ends so as to force equal movements and total compression on to the pipes, resulted in non-representative measurements of force distribution between the outer and inner pipes.

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