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Plugging, set-up effects and load capacity of open-ended pipe piles

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ABSTRACT: Load capacity assessment of driven open-ended steel pipe piles has uncertainties and requires some assumptions. These include degree of plugging, end bearing resistance, external and internal shaft friction resistances and time-delayed set-up effects. The available end bearing resistance or the internal shaft friction resistance of a partially plugged pipe pile will depend on the relative stiffness of the soil plug. This paper discusses the results of published full-scale test results on instrumented piles. This paper also discusses the set-up effects observed during dynamic testing of 610 mm, 760 mm, 1200 mm and 1500 mm diameter pipe piles. Some of the piles were subjected to dynamic testing about 5.5 months after their installation to assess the set-up effects. The results showed that it may take about 2 to 3 months for the set-up effects to occur in an environment where lot of piling activities taking place.

1 INTRODUCTION

Driven large diameter open-ended steel pipe piles are often the preferred pile type in areas close to water bodies due to their structural load capacity, ease of installation and achieving required penetration or founding depth. Assessment of the load capacity of open-ended pipe piles is a difficult problem and has uncertainties. These include the assessment of degree of plugging, mobilised end bearing resistance, external and internal shaft friction resistances and time-delayed set-up effects.

Assessment of the end bearing resistance in open-ended pipe piles is often difficult due to the complicated behaviour of soil plugging. The ICP Design Method (Jardine et al. 2005) indicates that a pipe pile would not plug, if one of the following two conditions is applicable:

- D_i $0.02\,(D_r - 30)$
- D_i $0.03\,q_c$

Where, D_i is the internal pile diameter in metres, D_r is the relative density in percent and q_c is the average cone tip resistance in MPa over a specified depth range near the pile toe.

The soil inside a large diameter open-ended pile may be ‘partially plugged’ during driving (i.e. top of plug moves down by an amount less than the pile penetration), rather than ‘unplugged’ (i.e. top of plug remains at the same elevation during driving). The soil plugs of the partially plugged piles during driving may also behave as ‘fully plugged’ during static load testing (i.e. no relative movement between the plug and pile shell), once the excess pore pressures generated during driving are dissipated.

Randolph et al. (1991) presented a theoretical approach to assess the resistance provided by the soil plug and verified the approach with experimental and numerical assessments. The experimental assessment involved testing of 100 mm internal diameter pipe piles in the laboratory and pushing soil plugs up to 1.5 m long within the pipe using a piston. A plug displacement of more than 100 mm (i.e. more the pile diameter) was required to mobilise the ultimate resistance of the soil plug. Test results indicated that a plug toe displacement about 30% to 40% of the plug diameter may be required to mobilise plug resistances of practical interest. They have also discussed the undrained and drained behaviour of the soil plug. An undrained behaviour will be prevalent during driving due to the high excess pore pressures generated during driving. However, during long term static loading a drained behaviour may be applicable.

Behaviour and load capacity of the open-ended steel pipe piles has been studied by several researchers in the past (e.g. Lehane & Gavin, 2001, Paik et al., 2003, Jardine et al. 2005, Xu et al., 2008, Yu & Yang, 2012, Jeong et al. 2015).

Jeong et al. (2015) stated that existing methods of assessing load capacity of open-ended pipe piles have some limitations as they are mostly based on correlations derived from model pile tests of small diameter piles. They presented the results of field load tests on three instrumented large diameter piles.

This paper presents an assessment of the mobilised internal and external shaft friction, annulus end bearing and soil plug end bearing resistances.

This paper also discusses the set-up effects observed during dynamic load testing of 610 mm, 760 mm, 1200 mm and 1500 mm diameter pipe piles for a port project where the author was involved in a review capacity. Set-up effect was the key factor in the load capacity verification of those piles. Some of the piles were subjected to dynamic load testing about 5.5 months after their installation.

2 PILE PLUGGING AND LOAD CAPACITY

The conditions of unplugged, partially plugged and fully plugged conditions in a pipe pile is illustrated in Figure 1. The key aspect in defining the pile plugging condition during driving is the increment in plug length with respect to increment in pile penetration, but this is generally not measured. Most often, the plug length is only measured at the end of driving. If the plug length is less than the pile penetration, the pile is at least partially plugged.

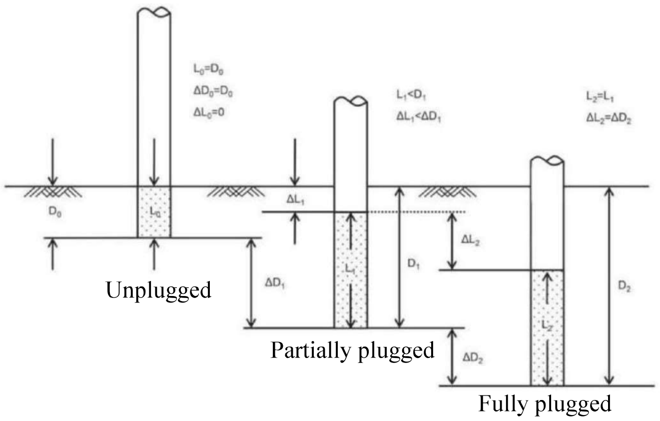

Figure 1. Pile plugging conditions (adapted from Ko and Jeong, 2015).

The shaft and bearing resistances that can develop in an open-ended pipe pile contributing to its load capacity are shown in Figure 2. The contribution from the soil plug will be the lesser of the base resistance of the soil plug (Q_{base})or the internal shaft friction (Q_{in}).

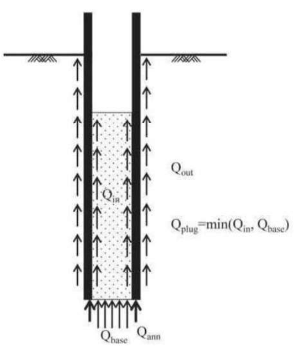

Figure 2. Components of load capacity in pipe pile (adapted from Ko and Jeong, 2015).

3 PUBLISHED FIELD LOAD TESTS

Jeong et al. (2015) presented the field load testing results of three double walled instrumented pipe piles in sand. The outer diameters of the tested piles were 914.4 mm (inner pile 812.8 mm), 711.2 mm (inner pile 609.6 mm) and 508.0 mm (inner pile 406.4 mm). The inner and outer piles were welded at the top and bottom. A summary of the test piles depths and soil conditions is presented in Figure 3.

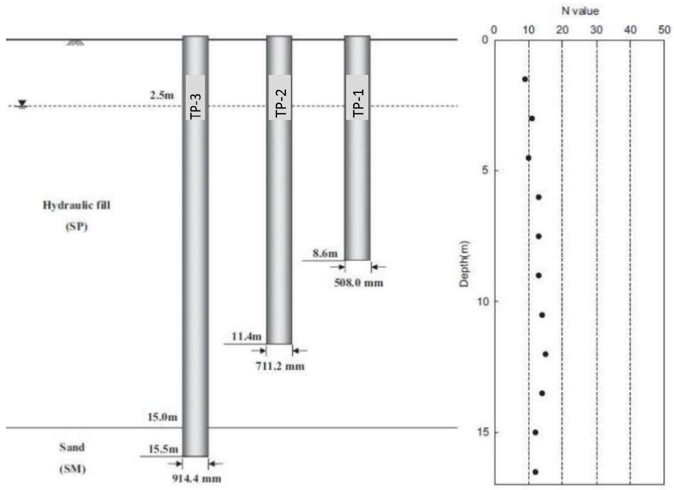

Figure 3. Details of test piles and soil conditions (adapted from Jeong et al., 2015).

All test piles were partially plugged during driving. The incremental plug depth ratios (L_1/ D_1 in Figure 1) at the end of driving were about 0.8, 0.4 and 0.4, for test piles TP-1, TP-2 and TP-3, respectively. The total plug lengths at the end of driving were 45%, 77% and 85% of pile penetration for test piles TP-1, TP-2 and TP-3, respectively. The piles were subjected to dynamic and static load testing. The results of the static load testing are shown in Figure 4. The load capacities obtained from dynamic load testing were indicated to be similar to those obtained from static load tests.

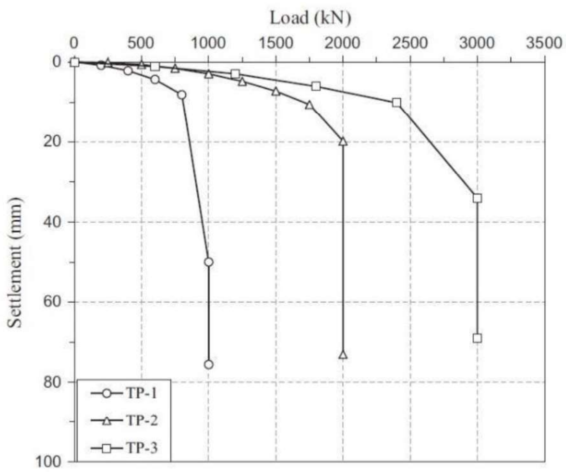

Figure 4. Results of static load tests (adapted from Jeong et al., 2015).

The distribution of the axial loads on the internal and external pipes of the 508 mm diameter pile, which were obtained from strain gauge measurements are shown in Figure 5(a) and (b). The distribution of the axial loads for other two piles were similar. Figure 5(a) indicates that the pile behaved as fully plugged pile (i.e. no relative movement between the soil plug and internal pile wall to about 7.5m depth).

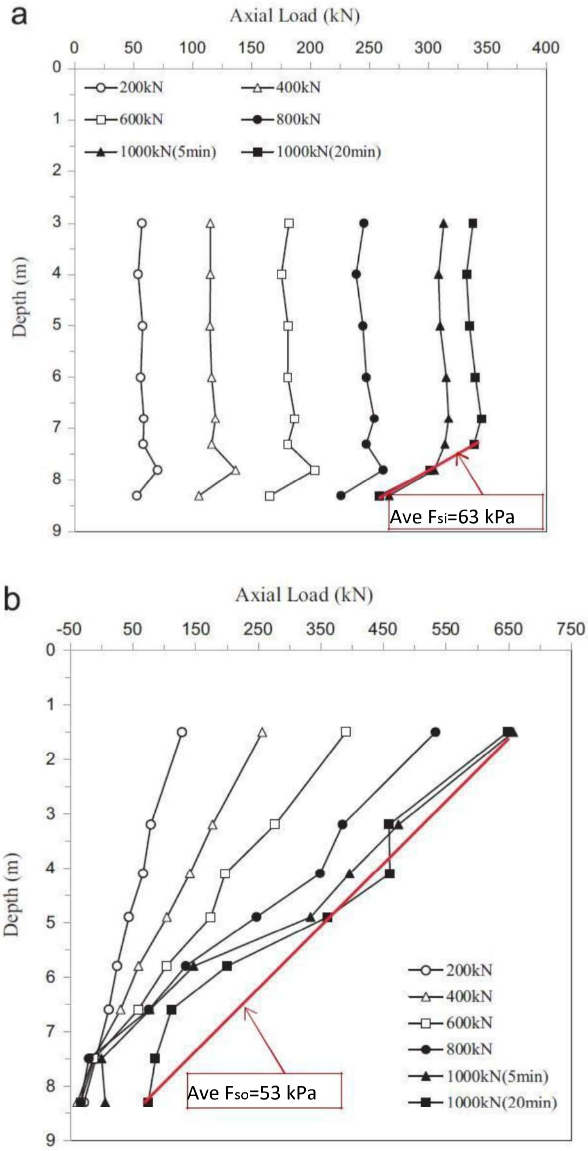

Figure 5. Axial load distributions on (a) inner and (b) outer pipes for 508 mm diameter pile (adapted from Jeong et al., 2015).

3.1 *Assessment of field load test results*

Based on the results presented in Jeong et al (2015), the author has assessed the mobilised internal (F_{si}) and external (F_{so}) shaft friction resistances (see Figure 5), end bearing resistance on the annulus and the end bearing resistance on the soil plug for all three test piles. An assessment of these resistances was not presented by Jeong and his co-workers in their papers.

The results of the assessment are shown in Figure 6. The mobilised end bearing resistance on the soil plug is equal to the total mobilised internal shaft friction. The mobilised end bearing resistance on the annulus is the difference between the total applied load and the mobilised external and internal shaft friction. The plug lengths and extents of internal shaft mobilisation within the soil plugs are also illustrated in Figure 6, which vary between about 1.2 m to 2.5 m.

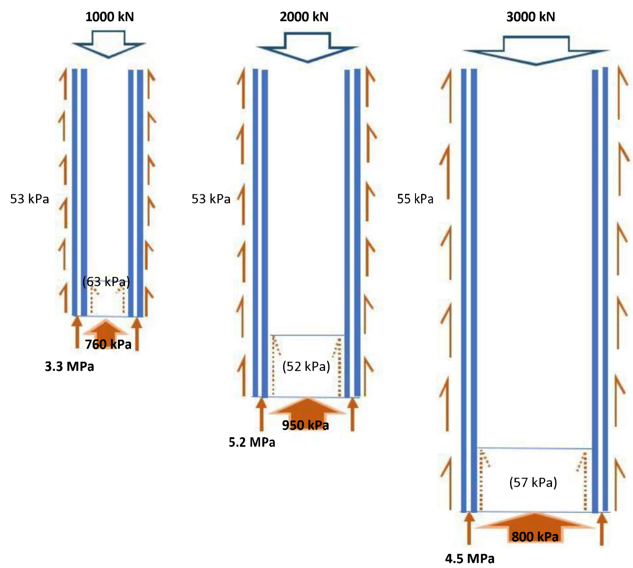

Figure 6. Components of load capacity in test piles.

The average internal and external shaft friction resistances were similar in all the test piles and ranged between 53 kPa and 57 kPa, except in the internal shaft resistance in the smaller diameter pile (TP-1), which was slightly higher. This may be due to densification in the soil plug and the associated arching/dilation effects.

The length of internal shaft mobilisation is governed by the toe resistance mobilised on the soil plug, which vary from about 760 kPa to 950 kPa.

3.1.1 *End bearing resistance*

The mobilised end bearing resistance in the pile annulus ranged between about 3.3 MPa to 5.2 MPa, which is within the range of ultimate end bearing resistance typically expected for a closed-ended pipe pile driven into medium dense sands with SPT N values ranging from about 12 to 15.

As it can be seen on Figure 6, the mobilised end bearing resistances in the soil plugs are significantly lower than those in the pile annuluses (by a factor of about 5). This is due to the difference in the stiffnessess between the pile shell and the soil plug. One dimensional analysis of soil plug compression as outlined in Randolph et al. (1991) may suggest a plug modulus in the range of 15 MPa to 25 MPa, which is not unreasonable of the medium dense sands at the site.

The test results indicate that the piles are behaving as ‘fully plugged’ piles and the mobilised end bearing resistance on the soil plug is lower than that on the pile annulus due to the lower stiffness of soil plug compared to the pile shell.

The maximum pile displacements during testing were about 70 mm to 75 mm, which are about 18.5%, 10.1% and 8.6% of the pile plug diameters for test piles TP-1, TP-2 and TP-3, respectively. These are considerably less than 30% to 40% indicated by Randolph et al. (1991) for mobilisation of plug resistances of practical interest. However, it should be noted that for a 900 mm diameter pile, a 40% displacement is about 360 mm and testing a pile with this order of magnitude of displacement may not be practical.

4 SET-UP EFFECTS

The excess pore pressures generated during pile driving will have a significant effect on the load capacity of the pipe piles, which should be carefully considered, if the pile load capacity is to be verified by dynamic load testing. The generation of the excess pore pressures during driving and their dissipation after the end of driving will depend on many factors including the length of the pipe pile, subsurface soil profile, presence of clay layers, and construction activities in the vicinity (for example, installation of additional piles).

Foyn & Rongved (2009) presented the results of load testing of a 23 m long, 900 mm diameter pipe pile in clay and silt materials 13 years after of its installation. Static load test of the pile 25 days after the installation verified a maximum load capacity of 2260 kN at a displacement of 42 mm. This was considerably lower that the estimated design load of 4300 kN. The pile was tested again 13 years after installation and a maximum load capacity of 6240 kN was verified at a displacement of 87 mm. This illustrates that considerable set-up effects occur, especially in fine grained soils.

4.1 *Port project, Melbourne, Australia*

In a port project in Melbourne, Australia, the set-up effects were found to have significant effects in verifying the load capacities of the pipe piles. Kristinof & Thorn (2017) presented the set-up effects on the piles from this project, but from a slightly different point of view.

The project involved construction of new wharf involving 1500 mm diameter (25 mm wall thickness) pipe piles with sheet piles forming the front edge of the wharf and 1200 mm diameter (20 mm wall thickness) raked pipe piles at the rear providing the anchorage. The wharf deck was supported on driven 350 mm square precast concrete piles. Figure 7 shows a typical cross section of the wharf.

The subsurface conditions at the port project site typically comprised fill and loose to medium dense sands (PMS), underlain by soft to firm silty clays (CIS), underlain by stiff to very stiff silty and sandy clays (FBS), underlain by a mixture very stiff sandy/silty clays and medium dense to dense silty sands and gravels. The thicknesses of the soil units were variable across the site. The piles were founded below about 30 m depth in the soil unit comprising a mixture very stiff sandy/silty clays and medium dense to dense silty sands and gravels. Typical subsurface profile is also shown in Figure 7. The abbreviations of the subsurface units refer to the local names of the subsurface units.

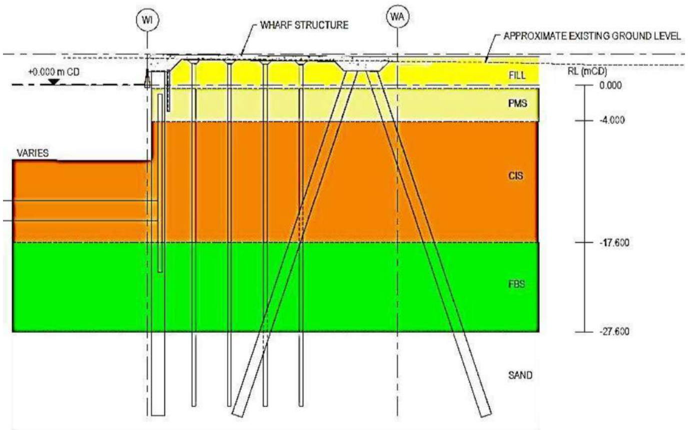

Figure 7. Typical cross section of the wharf.

4.1.1 *760 mm diameter test piles*

The 760 mm diameter (16 mm wall thickness), test piles were driven to about 33.5 m depth. The test piles were subjected to dynamic load testing at the end of driving and 7 days after installation as well as static loading testing.

The maximum load verified by static load testing was 4000 kN at a displacement of about 70 mm. The maximum load capacity verified by dynamic load testing and CAPWAP analysis was 4600 kN. It should be noted that the test pile shafts were not instrumented and the static load tests provide the total load capacity only. The CAPWAP analysis of the dynamic load testing provided a representative distribution of the shaft resistance along the pile and the end bearing resistance, but it does not provide contributions from the internal and external shaft resistances and the contributions from pile annulus and pile plug end bearing resistances.

The end bearing resistance mobilised at the end of driving was in the range of 10.5 MPa to 16.2 MPa, based on pipe annulus area (0.9 MPa to 1.3 MPa over full end area). The end bearing resistance mobilised during 7-day restrike was in the range of 5.4 MPa to 9.6 MPa, based on annulus area (0.5 MPa to 0.8 MPa over full end area).

The average shaft friction resistance (when considering the outer shaft area only) below the soft clay layer (below 9 m depth) was in the range of 23 kPa to 27 kPa at the end of driving and was in the range of 60 kPa to 75 kPa at 7-day restrike. There was considerable increase in the shaft friction resistance over 7 days.

It should be noted that test piling program was carried out at an early stage when there was no other construction activity on the site.

4.1.2 *1.2 m and 1.5 m diameter production piles*

Based on the results of test piles, 1.2 m diameter piles, which have the largest axial load requirement in the design, were designed for a maximum ultimate load capacity of about 11.3 MN, when founding at similar depths as the test piles. However, testing of the 1.2 m and 1.5 m diameter piles, installed at the early stages of the construction program, 7 to 18 days after their installation, showed load capacities lower than 6 MN. The mobilised shaft friction resistances were considerably lower than those observed in the test piles.

Testing of these early stage piles after about a month showed an increase in the load capacity, but still lower than the design requirement. Subsequent hammer blows during restrike were also found to reduce the load capacity. Figure 8 shows the shaft friction distribution (from CAPWAP) of a 1200 mm diameter pile at end of driving and at various hammer blows (Blow 2 through Blow 208) during a 32-day restrike.

The end bearing resistances (14 MPa to 63 MPa) indicated at the bottom of the graphs are based on pile annulus area only. If the full pile area is considered, the end bearing resistances will be in the range of 0.9 MPa to 4.9 MPa. If the end bearing resistance of the annulus area is limited to 20 MPa, which is considered reasonable based on the CPT data, then the end bearing resistance in the soil plug area will be in the range of 0.5 MPa to 3.8 MPa. These end bearing resistances are similar to that indicated in Matsui (2005). That is, the end bearing resistance of large diameter open-ended pipe piles verified by dynamic load testing is only about 30% compared to that of a closed-ended pile.

Figure 8 also shows the gradual degradation of shaft friction resistance during restrike with further hammer blows, which is inferred to be due to gradual increase in excess pore pressures.

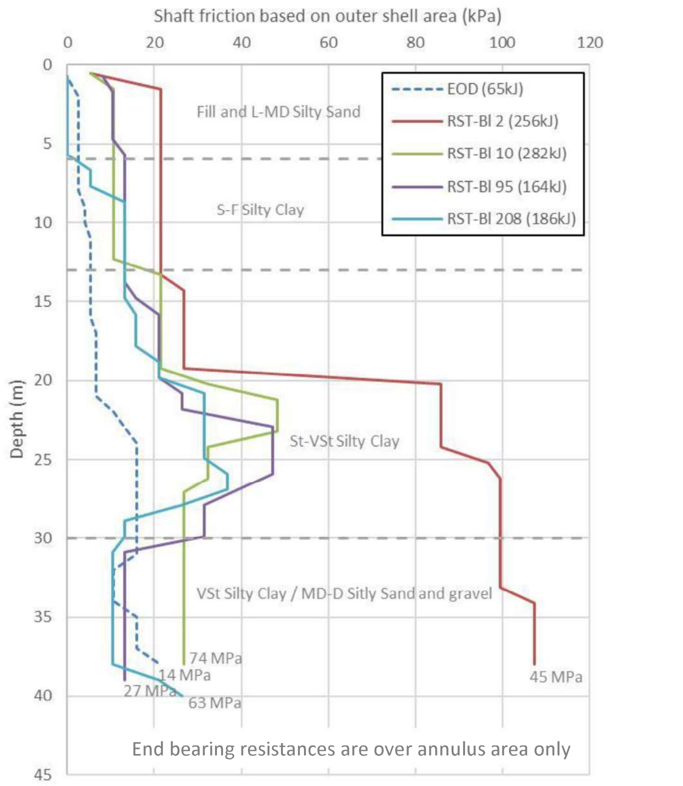

Figure 8. Shaft friction and end bearing resistance in a 1200 mm diameter pipe pile.

4.1.3 *Set-up effects on shaft friction*

The project also involved driving of sheet piles and many precast concrete piles in the area for the construction of a new wharf. These intense pile driving activities inferred to have delayed the dissipation of the excess pore pressures generated during driving of the pipe piles and the set-up effects.

To further assess the potential set-up effects, the test piles, which were in an area away from the early construction work, were subjected to dynamic testing again, about 5.5 months after their installation. The static load testing of the test piles required the installation of 610 mm diameter steel pipe piles as reaction piles. Some of these reaction piles were also tested 5.5 months after their installation. The average shaft friction resistance below the soft clay layer (when considering the outer shaft area only) was in the range of 70 kPa to 120 kPa, which was on average about 25% higher than that obtained during the 7-day restrike.

Figure 9 presents a summary of the variation of the average shaft friction resistance below the soft clay layer (when considering the outer shaft area only) with time for all the pipe piles tested. The results of the test piles and the reaction piles are shown as open symbols on the figure. The closed circle symbols represent various production piles subjected to testing. The improvement of shaft friction resistance with time for one selected production pile (WH031) is also shown as dashed line in Figure 9.

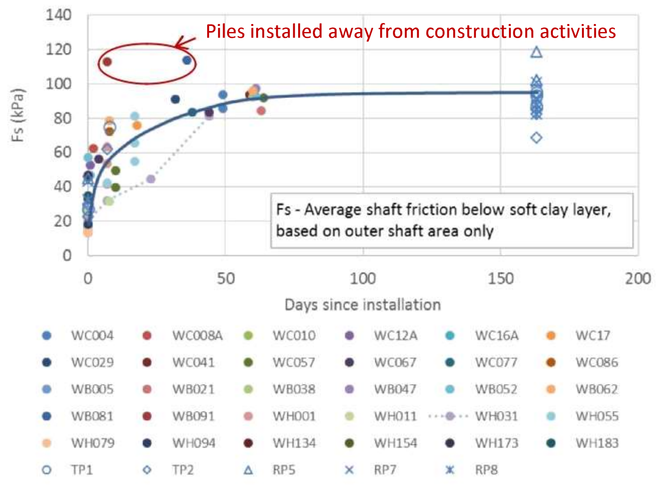

Figure 9. Variation of average shaft friction with time.

The shaft friction results shown in Figure 9 suggest that set-up effects may take about two months or more in a construction environment encountered at the site.

Some of 1200 mm diameter pipe piles were installed well ahead of schedule, away from the area heavy construction activities. Testing of these piles indicated that the set-up effects have occurred within much shorter times.

5 CONCLUSIONS

The following conclusions can be made from the information presented in the paper.

- Large diameter open-ended pipe piles are most likely to behave as partially plugged during driving.
- The soil plugs in partially plugged pipe piles during driving may behave as 'fully plugged' during static loading, once the excess pore pressures generated during driving are dissipated.
- The mobilised toe resistance in the soil plug, will be significantly lower than the toe resistance on the pile annulus due to the difference in the stiffnesses of the soil plug and the pile shell.
- In large diameter open-ended pipe piles, it is not possible to verify/mobilise the full soil plug resistance during dynamic load testing due to the magnitude of the displacement required.
- The soil plug resistance to be considered in a pipe pile design should consider the relative stiffness of the soil plug and pile shell and the practicality of its verification.
- In large diameter open-ended pipe piles, the mobilised end bearing resistance during dynamic load testing may only be about 30% of that of a closed-ended pile.
- The set-up effects will depend on many factors including the length of the pipe pile, subsurface soil profile, presence of clay layers, and construction activities in the vicinity.
- In areas of heavy construction activity, the time for set-up effects to occur may be significantly higher than that observed in any test pile program carried out prior to construction.

6 ACKNOWLEDGEMENT

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