

Indicative side resistance of bored piles socketed into Makassar claystones

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ABSTRACT: An elevated tollway in Makassar, Indonesia used bored piles socketed into claystones to support the bridge structures. A part of the quality control program, 108 high-strain dynamic pile tests, accompanied by signal matching analyses, were performed. Based on comparison with results of static pile load tests, these dynamic pile load tests provide relatively reliable resistance indications for rock sockets in claystones with very low to low strength. Based on the signal matching analyses, the indicative side resistance and its derivative factor obtained from the subsequent signal matching analyses tend to be the lower bound of the typical design recommendations; a reduction factor is also reported. The indicative side resistance is evaluated against the claystone UCS and RQD. The indicative side resistance is found to be not significantly affected by the socket length and diameter. The general statistics of the side resistance parameters is reported as well.

KEYWORDS: Bored piles, rock sockets, claystones, high-strain dynamic pile test, signal matching analysis, side resistance.

1 INTRODUCTION

A 4.3 km long, elevated tollway in Makassar, Indonesia used bored piles socketed into claystones with very low to low strength to support the bridge structures; the claystones were overlaid by soil layers with varying thicknesses. Of the more than 900 bored piles, the diameter of bored piles for the main structure piers was 1.2 m, while that for the ramp structure piers was 1.0 m. The bored piles were socketed into the claystones to achieve the targeted capacities, and therefore, one of the design questions was how much side resistance the claystone sockets could provide.

The side resistance was estimated using the prediction model proposed by Kulhawy et al. (2005) that was subsequently adopted in AASHTO LRFD Bridge Design Specifications (2020). The side resistance in this approach was estimated based on the uniaxial compressive strength (UCS) along the sockets. It is noted that the information available in the literature for the socket side resistance is rather limited due to its empirical nature, and this has led to continuing discussions on this topic in the literature (e.g., Rezazadeh and Eslami 2017, Asem and Gardoni 2019). In addition, AASHTO (2020) also has an additional clause to consider the effect of different rock conditions on the side resistance.

Ideally, the actual side resistance is verified based on results of instrumented sockets under static axial compression or tension loads (e.g., Prakoso & Kulhawy 2002). However, these tests are conducted typically in a very limited number of tests because of technical, schedule, and cost issues. Alternatively, for sockets in claystones with low strength, high strain dynamic pile load tests and subsequent signal matching analyses could be employed to verify indirectly the side resistance (e.g., Turner 2006). By adopting this approach, a large number of tested sockets would then be feasible.

The objectives of this paper are to evaluate 1) whether the high strain dynamic pile load tests would provide relatively reliable resistance indications of rock sockets in claystones with very low to low strength, and 2) whether the side resistance obtained from these tests and subsequent signal matching analyses would be within the typical design recommendations. The results of 108 high strain dynamic pile load tests are evaluated, and the side resistance from the subsequent signal matching analyses is also evaluated. The side resistance along the sockets is determined by including the top of claystone depth information obtained from the actual drilling records. The resistance is also verified based on the results of static pile

load tests. The side resistance is correlated with the rock parameters and rock socket length. In addition, the practical implications of the findings are discussed.

2 DATA

2.1 Rock data

The rock data for the 108 tested piles are summarized in Figure 1. The intact rock, uniaxial compressive strength (UCS) values shown are the mean UCS values from the rock samples tested along the rock sockets. Typically, there were two UCS data for each pier of the main structures, but the number of UCS data for the piers of the ramp structures was somewhat more limited. The rock quality designation (RQD) values shown are the geometric mean values of RQD along the rock sockets. It can be seen that there is no particular trend correlating the mean UCS and the geometric mean RQD.

The mean and standard deviation of the mean UCS values are 6.1 MPa and 1.4 MPa, respectively; the coefficients of variation (CoV = standard deviation / mean) is 23.1%. The range of UCS values is within rocks with very low strength (less than 5 MPa) to low strength (between 5 MPa and 25 MPa). This CoV value indicates that the variability of the claystone is relatively on the high side (e.g., Phoon et al. 2016). The mean and standard deviation of the geometric mean RQD values are 63.2% and 16.1%, respectively; the CoV is 25.5%.

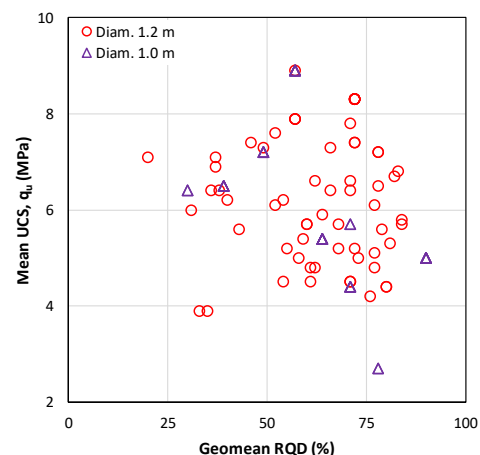


Figure 1. Distribution of mean UCS and geometric mean RQD for 108 tested rock sockets.

2.2 Rock socket length data

The rock socket length data for the 108 tested sockets are summarized in Table 1 (mean \pm standard deviation; minimum and maximum). The top of rock is $7.6 \text{ m} \pm 3.3 \text{ m}$. The length was determined primarily by considering the structural loads and claystone UCS. In general, the sockets for the piers of the main structures are longer than those for the piers of the ramp structures. It is noted that all bored piles were constructed by one world-renowned bored pile company, and therefore the quality variability of these bored piles is expected to be relatively low. It is noted that the nominal concrete strength f'_c of the bored piles is 25 MPa.

Table 1. Summary of rock socket geometry.

Diameter (m)	No. piles	Rock socket length (m)
1.2	64	9.0 ± 3.7 (2.0 – 17.6)
1.0	44	7.8 ± 2.6 (2.1 – 12.5)

2.3 High strain dynamic pile load tests and associated signal matching analyses

All the high strain dynamic pile load tests were performed according to ASTM D4945-12 (ASTM 2012). Two companies performed the tests; one company performed 103 tests evaluated, while the other company did only 5 tests evaluated. As most of the tests evaluated was performed by one company, the quality variability of these tests is expected to be relatively low. Both companies used a drop hammer of about 150 kN.

Following all pile load tests, both companies performed a numerical signal matching analyses using software CAPWAP. All the CAPWAP input data were first corroborated by checking against the design data and drilling records. Therefore, the CAPWAP modeling could at least be performed with some level of confidence.

It is highlighted that the nominal concrete strength f'_c of 25 MPa is much greater than the mean UCS of 6.1 MPa. Therefore, it is argued that the one-dimensional wave propagation assumed in the high strain dynamic pile load tests, as well as the signal matching analyses, could be satisfied.

2.4 Static pile load tests

There were two (2) conventional static and one (1) fully instrumented, bi-directional static axial compressive pile load tests that were performed in piers with a high strain dynamic pile load test. The conventional tests were performed according to ASTM D1143-07 (ASTM 2007), employing the reaction pile system. The bi-directional test was performed according to ASTM D8169-18 (ASTM 2018).

3 DATA EVALUATION

3.1 Static load tests and comparative evaluation

The bi-directional static axial compressive pile load test would provide “actual” side resistance values. The results indicated that the bored pile had not developed its full side tip or “ultimate” resistances (i.e., the side resistance still increasing with upward displacement for the top part and with downward displacement for the bottom part). The top part segments indicated side resistance values of between 70.1 kPa and 196.1 kPa, while the bottom part segment indicated side resistance value of 461.4 kPa. The weighted mean value of the side resistance is 176.6 kPa. Though not the “ultimate”, these values could be used as an indicator in the further evaluation.

The pile settlement-load curves generated from the signal matching analyses (CAPWAP) are compared with the curves obtained from the conventional static pile load tests for a bored

pile in Pier P9 and a bored pile in Pier P48. For each pier, the actual bored piles tested dynamically and statically were admittedly different piles. Nevertheless, it is argued that they could at least provide indications regarding the two different test types. The results are shown in Figure 2. It can be seen that the capacity performance of the simulated curves is somewhat lower than that of the curves from the static pile load tests, indicating that the results of the signal matching analyses would be apparently conservative.

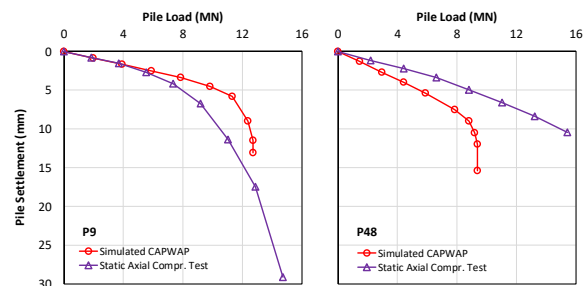


Figure 2. Comparative evaluation of results of static pile load tests and results of software simulations.

3.2 Indicative side resistance

The side resistance for each depth obtained from the signal matching analyses was thought to be more indicative, instead of “actual” side resistance. Therefore, for each socket, the side resistance for each modeling segment was not directly used, but the mean side resistance was calculated for the socket length. The socket length was determined based on the actual drilling record. In some cases, there were weathered claystones overlying the claystones, and they were characterized simply by assuming side resistance greater than 100 kPa but not identified as claystones in the drilling record. An example of this process is shown in Figure 3.

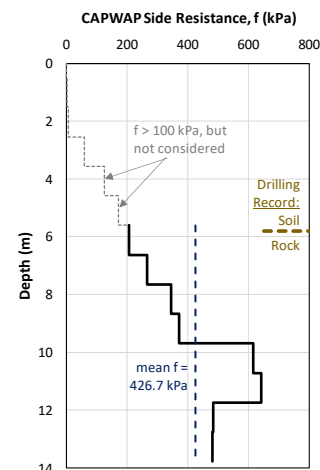


Figure 3. Generalized determination of indicative side resistance.

The indicative side resistance for the 108 rock sockets is summarized in Table 2, and the histogram of these data is shown as Figure 4. The mean and standard deviation of all data are given, as well as the minimum and maximum values. The CoV of all the indicative side resistance is about 30%.

Table 2. Summary of indicative side resistance.

Diameter (m)	No. piles	Indicative side resistance (kPa)
1.2	64	356.7 ± 112.6 (164.2 – 692.5)
1.0	44	325.5 ± 84.7 (179.6 – 531.1)
All	108	344.0 ± 102.9 (164.2 – 692.5)

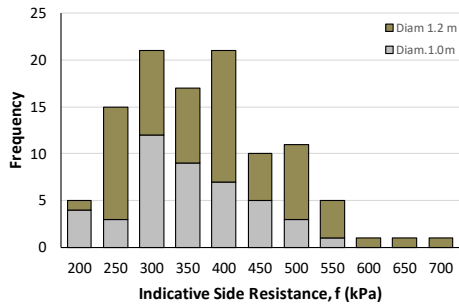


Figure 4. Histogram of indicative side resistance for both 1.2 m and 1.0 m rock sockets.

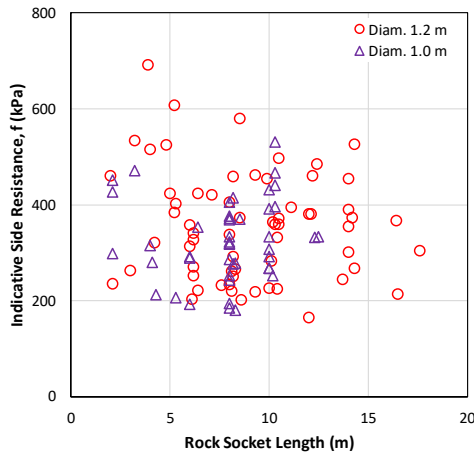


Figure 5. Indicative side resistance versus rock socket length.

The indicative side resistance is evaluated against their respective rock socket lengths in Figure 5. The three highest side resistance values are observed in the relatively shorter socket length range. The other data appear to have no apparent trend between the side resistance and the socket length. In addition, the socket diameter appears to have no significant effects on the indicative side resistance as well.

The indicative side resistance is evaluated further by comparing the values with the respective mean UCS, as shown in Figure 6. The three highest resistance values are observed in the higher range of mean UCS. However, the plot of the indicative side resistance versus the mean UCS in general shows no apparent correlation.

The indicative side resistance is also evaluated against the resistance geometric mean RQD, as shown in Figure 7. The three highest values appear to have no specific range. Furthermore, the plot between the indicative side resistance and the geometric mean RQD shows no particular correlation.

In pier P6, six bored piles were dynamically tested. The socket indicative side resistance varied between 203.6 kPa and 692.5 kPa, with the mean and standard deviation of 399.4 kPa and 192.2 kPa (CoV = 48.1 %), respectively. In pier P10, three bored piles were dynamically tested. The side resistance varied between 201.5 kPa and 461.5 kPa, with the mean and standard deviation of 294.7 kPa and 144.8 kPa (CoV = 49.1 %), respectively.

3.3 Normalized indicative side resistance

The indicative side resistance is also evaluated by normalizing it by the respective mean UCS, named as the side resistance factor α_r , as given by Equation (1).

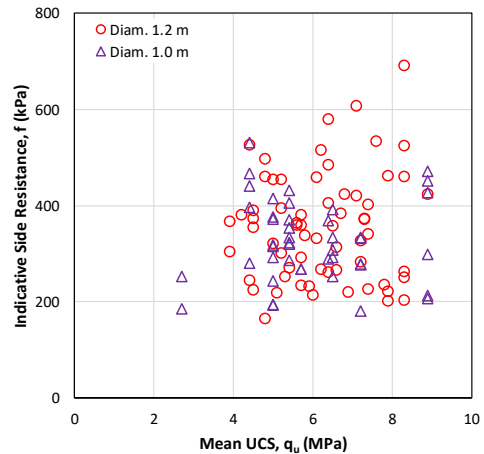


Figure 6. Indicative side resistance versus mean UCS.

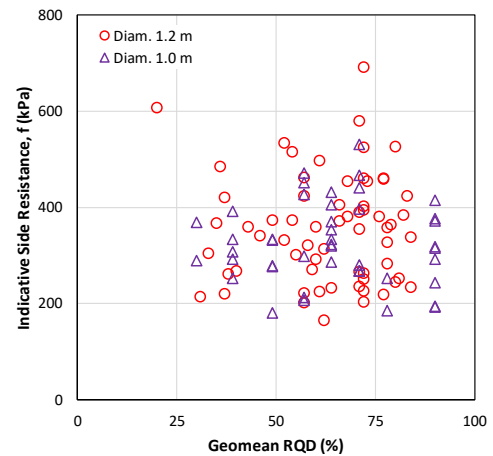


Figure 7. Indicative side resistance versus geometric mean RQD.

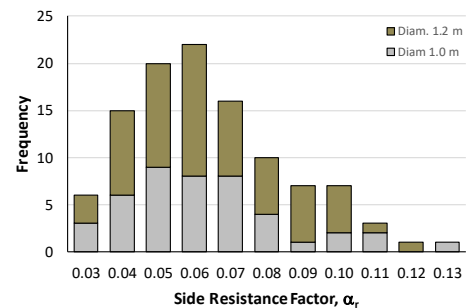


Figure 8. Histogram of side resistance factor α_r for both 1.2 m and 1.0 m rock sockets.

$$\alpha_r = f_{indicative} / UCS_{mean} \quad (1)$$

The histogram of these data is shown as Figure 8. The resistance factor α_r varied between 0.023 and 0.121, with the mean and standard deviation of 0.059 and 0.021, respectively. The CoV of all the indicative side resistance is about 36%. The plot between the normalized resistance and the mean UCS (normalized by the atmospheric pressure) is shown as Figure 9.

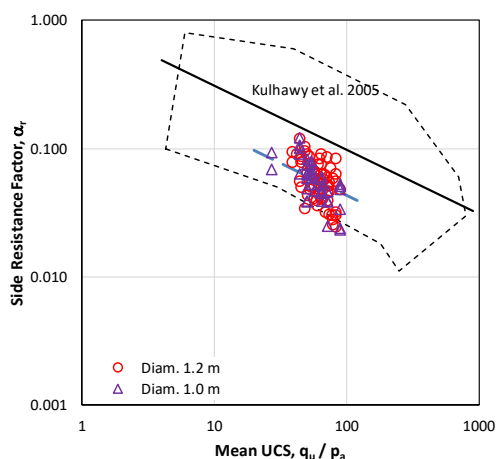


Figure 9. Side resistance factor α_r versus mean UCS.

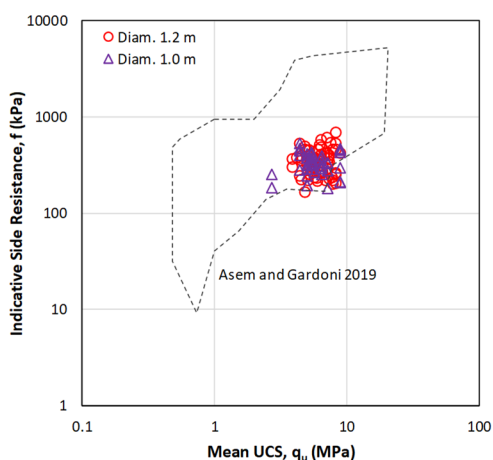


Figure 10. Comparison with study on rock sockets in weak sedimentary rocks by Asem and Gardoni (2019).

4 DISCUSSION

The reliability of the indicative side resistance needs to be evaluated. The minimum indicative side resistance is 164 kPa, which is relatively similar to the weighted mean side resistance observed from the bi-directional static axial compressive pile load test of about 176 kPa. As previously discussed, the latter value is thought to be not the “ultimate” resistance, as the resistance would still increase with increasing socket displacement. This suggests that the minimum or lower bound indicative side resistance is not too high.

The mean indicative side resistance is 344 kPa. This value is lower than the maximum side resistance observed from the bi-directional pile load test of about 461 kPa; again, the latter is thought to be not the “ultimate” resistance. This suggests that the mean indicative side resistance is within a reasonable range.

The reliability is further evaluated by referring to Asem and Gardoni (2019) specifically discussing rock sockets in weak sedimentary rocks. Their database (area with dashed line) is compared with that in this study in Figure 10. In general, the 108 indicative side resistance data falls within their database, but the data appears to be the lower bound of their database. This suggests that the indicative side resistance from signal matching analyses tend to be conservative.

Asem and Gardoni (2019) furthermore indicate that the side resistance tends to decrease with increasing rock socket length for lengths from 0.5 to 3.0 m, and that the side resistance becomes more independent of socket lengths greater than 3.0 m. In this study, the rock socket lengths varied from 2.0 m to

17.5 m, and the indicative side resistance appears to be independent of the socket lengths, as shown in Figure 5.

The side resistance factor α_r from Kulhawy et al. (2005) is also shown in Figure 9. It can be seen that the factor α_r from this study tends to be the lower bound of their factor database (area with short dashed line). The approach in AASHTO (2020), in which a reduced factor α_r is introduced, is adopted as well as shown in Figure 9 (long dashed line). To match the current factor α_r with the AASHTO design factor, a reduction factor of 0.44 may be used.

The reduced factor α_r in AASHTO (2020) is linked to the RQD of the rock mass. However, in this study, the side resistance factor α_r appears to be independent of the geometric mean RQD. Therefore, the reduction factor of 0.44 is not thought to be RQD-based.

The histograms of the indicative side resistance (Figure 4) and the side resistance factor α_r (Figure 8) appear to be of log-normal type probability density functions. The CoV values of both the resistance (30%) and the factor (36%) are somewhat greater than the CoV values of the mean UCS (23%) and geometric mean RQD (26%). Furthermore, for isolated piers, the mean indicative side resistance could be less or greater than that of the entire database, while the associated CoV (48-49%) was found to be greater than that of the database.

5 CONCLUSIONS

This study showed that the high strain dynamic pile load tests would provide relatively reliable resistance indications for rock sockets in claystones with very low to low strength. This study also showed that, from 108 pile tests, the indicative side resistance and its derivative factor obtained from the subsequent signal matching analyses tend to be the lower bound of the typical design recommendations; a reduction factor is also reported. The indicative side resistance was correlated to the socket length and diameter, as well as the rock parameters. The statistics of the side resistance parameters is reported.

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