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Review of Singapore Old Alluvium bored pile design based on pile test data

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ABSTRACT: About a third of Singapore is underlaid by the Old Alluvium (OA) foundation, and it occurs extensively to the east of the island. The OA is highly variable being typically medium dense at the top where its surface has been eroded and with increasing strength and over-consolidated at depth. The top of the OA is generally undulating with abrupt changes in elevation. These variabilities, as well as its grain composition varying from sand to gravel to clays makes geotechnical modelling for foundation design challenging. Preliminary bored pile tests have been carried out during recent construction of MRT Stations and other Singapore projects. In this paper, we present collated preliminary pile test data with mobilised shaft friction (fs) values for OA. It reviews the standard correlation of fs with SPT ‘N’ commonly adopted in Singapore practice. Based on this review, an alternative design methodology was proposed in compliance with Eurocode 7. The methodology was then adopted for the Paya Lebar Central project, which is founded on bored piles installed up to 80m below ground level. The selected shaft friction parameters and the preliminary pile test results are discussed in terms of the advantages of the methodology to minimise contractual/technical risk during construction.

RESUME: Les alluvions anciennes (OA) se trouvent abondamment dans l’est de l’île avec environ un tiers de Singapour composé par cette formation. L’OA est très variable, typiquement moyennement dense au sommet où sa surface a été érodée dans le passé et avec une résistance accrue et une surconsolidation en profondeur. Le sommet de l’OA est généralement ondule avec des changements abrupts de niveau. Cette variabilité ainsi que sa composition de grains variant du sable au gravier en argile rend sa modélisation géotechnique pour la conception des fondations difficile. Des tests préliminaires de pieux forés ont été effectués lors de la construction récente de stations de MRT et d’autres projets de construction à Singapour. Cet article présente ces résultats en comparaison avec les valeurs de frottement (fs) obtenues en OA, et examine la validité et la corrélation entre fs et le standard SPT ‘N’, généralement adopté à Singapour. Sur la base de ces données, une autre méthodologie a été proposée conformément à l’Eurocode 7 pour le choix des paramètres de frottement. Cette méthodologie alternative a été adoptée lors de la conception de Paya Lebar Central qui est fondée sur des pieux forés installés jusqu’à 80 m sous le niveau du sol. Les données de ce projet sont présentées, en particulier les avantages contractuels et techniques.

KEYWORDS: Singapore bored pile design, bored pile test data, Old Alluvium, shaft friction parameters

1 INTRODUCTION

In geotechnical engineering, the design of deep foundations often relies on empirical correlations. These are built through local experience and a continuous assessment of pile test results to fine tune the correlation factors. A key variable for parameters measured during pile testing is the quality of workmanship, the installation technique (e.g. driven, bored, jacked-in, etc.), and construction methods adopted. All these variables make the prediction of pile geotechnical capacities at design stage challenging for practitioners.

Although predictions for pile geotechnical capacities are typically verified with pile testing, this data is often unavailable at design stage. In Singapore, it is common practice to carry out pile testing just prior to installation and as part of the main piling contract. Therefore, piling contracts are tendered based on the engineer’s design length predictions. In our previous experiences, it has been shown that the accuracy of the predicted pile length can have significant cost implications for the project. Albeit, piling contracts are typically based on re-measurements.

Singapore’s heavy infrastructure and buildings are mostly founded on bored piles. A number of pile tests carried out at various locations of the island are therefore available. The work done for this paper focuses on reviewing the parameters for the Old Alluvium geological formation only. It presents the measured mobilised shaft friction values and assesses the validity of the empirical correlations with SPT ‘N’ commonly adopted in Singapore practice.

Based on this review, an alternative bored pile design methodology is proposed in compliance with Eurocode 7 for the selection of characteristic bored pile shaft friction parameters. This is presented by using the Paya Lebar Central project as a case study.

2 THE SINGAPORE OLD ALLUVIUM (OA)

The Old Alluvium (OA) is considered to be the oldest drift deposit in Singapore, consisting mainly of medium to very dense cemented clayey sand and fine gravels. It occurs extensively to the east of the island with about a third of Singapore underlain by this formation.

![Figure 1: Typical Section of Old Alluvium underlying the...](image-url)
Kallang Formation at Paya Lebar.

The OA is highly variable – typically medium dense at the top where its surface has been eroded in the past and with increasing strength and over-consolidation at depth. The top of OA is generally undulating with abrupt changes in elevation (observed up to 30m vertical and 100m horizontal). Figure 1 shows a typical variable profile of OA underlying the younger deposits of the Kallang Formation which is made up of marine clay and fluvial sands.

Figure 2 (left) shows a typical OA SPT ‘N’ profile increasing with depth, where ‘depth’ is indicated in meters below top of OA. Figure 2 (right) shows the variable nature of the OA in terms of its particle size distribution. This OA variability in terms of its variable top level, increasing strength with depth, and wide range of grain composition, makes its geotechnical modelling challenging.

3 TYPICAL OA BORED PILE PARAMETERS

It is well understood that bored pile shaft and end bearing parameters are greatly affected by the methods of construction. For example, bored piles constructed under bentonite slurry have measured shaft frictions that are about 50% of that measured on deep cased piles (K. Orihara et. al, 1998). Similarly, the end bearing is dependent on the contractor’s methods adopted for base cleaning just before concreting. Nonetheless, bored pile parameters are still required at design stage to predict pile lengths.

It is standard practice in Singapore to derive parameters for OA shaft friction ($f_s$) based on a correlation with the SPT N value. A correlation of $f_s$ = (2 to 3).N (Dr. Chang, 2005) and a ‘worst borehole approach’ to zone the pile design and derive embedment lengths is commonly adopted. In addition, two embedment criteria are specified; embedment into OA and into OA (N>100). As such, the design verification during construction includes the following steps: 1) Preliminary pile test to confirm the adopted correlation with N; 2) Specification of additional boreholes during construction to confirm top of OA and the SPT ‘N’ adopted for each piling zone. During installation, the depth of N>100 is verified by either additional boreholes or in most cases by observations and experience of the piling contractor/site engineer.

In relation to end bearing, it is worth noting that pile tests tend not to fully mobilise the base as test loads are often underestimated or tests are stopped once 10% (pile diameter) settlement is reached (e.g. due to soft toes). However, CE Ho 1994 has reported an ultimate value approaching 6MPa. Depending on base cleaning and contractor’s skill, values of up to 10MPa have been reported in the available pile test data. The end bearing in OA N>100 is typically limited to 5MPa to 6MPa for design.

4 OA MEASURED SHAFT FRICTION PARAMETERS

With the vertical and horizontal variability of the OA, previous experience has shown that the verification process during construction could lead to significant variations in pile length installed as compared to tender stage as they are dependent on the adopted correlation with N and the depth of N>100.

To review the bored pile design methodology, preliminary bored pile tests have been collated across the island. Figure 3 shows the locations superimposed in the geological map of Singapore. Out of the total number, 26 bored pile tests are available in the OA (mostly concentrated on the CBD area). The OA mobilised shaft friction data and associated N values have been taken as factual data directly from contractor’s reports. The interpretation of the pile test data was not described in this study. It is also worth pointing out that the majority of the bored pile tests presented have used bentonite as support fluid during construction. The testing method is either kentledge or O (or K)-Cells – the type of test is indicated in Figure 4 for reference.

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Figure 4: shows the N value vs OA mobilised shaft friction to review the correlation with N. Not surprisingly, the data shows a large variation ranging from 1N to 4N. The majority of the data plots between 2N and 3N, which is consistent with the correlations typically adopted (Chang, 2005). A general increased of shaft friction with N is noted.

Figure 5 shows the same data presented as mobilised shaft friction vs depth below the top of OA. This is consistent with the fact that theoretically, the increase in shaft friction should be a linear increase either based on effective stresses if the OA is sandier ($\beta \sigma''$) or undrained shear strength ($\alpha c_u$) if the OA is clay (Navfac, 1986). However, it would be impractical to establish a design approach based on sandier or clayey OA as this varies greatly within short distances, both laterally and vertically, making the site verification and zoning a difficult task. A correlation with N therefore represents a more practical approach for derivation of OA shaft friction, as the N value gives an indication of soil strength/stiffness parameters.

4 ALTERNATIVE DESIGN APPROACH

Based on the review of the pile test data and the observed shaft friction increasing with depth (see Figure 5), it is proposed to assess a particular project site based on all available SPT data and select a “characteristic” N design line as defined in Eurocode 7 (SS EN 1997-1:2010).

It should be emphasised that the SPT N value is also affected by the operator’s skills and equipment used (Bowles, 1988). Although N gives a good indication of the shear strength and deformation modulus of soils; it is not a direct measurement and therefore, an approach that assesses the site as a whole may be more appropriate than fine tuning the design to specific borehole and SPT data.

For cases where additional pre-drills/boreholes are carried out during construction, the new data can be plotted against the existing to ensure that the selected design line still represents a “characteristic” line. The site can be sub-divided into zones with specific N design lines as the designer sees fit based on his ground model and site assessment. A cautious estimate is however recommended to assess the level at which the OA N>100 is encountered. Based on the data reviewed, the lower bound shaft friction values do not reach 200kPa up until at least 20m to 25m below top of OA.

With the approach proposed, only a total embedment into OA is specified. Thus, it eliminates the need to verify the embedment into N>100 during construction; which realistically, cannot be easily established during pile boring.

5 CASE STUDY – PAYA LEBAR CENTRAL (PLC)

The proposed methodology was adopted during the design of Paya Lebar Central as shown in Figure 1 previously. PLC is founded on bored piles varying from 1.2m to 2.0m diameter. The piles were installed during 2016 up to 80m below ground level and embedded 30m to 40m into OA. The piling layout with the contours of top of OA are shown in Figure 6.

The SPT plots and selection of N “characteristic” line for Zone C are presented in Figure 7. A correlation $f_s=2.2N$ and end bearing of 6MPa was selected to derive ultimate pile capacities. Due to uncertainties in the correlation with N, the “characteristic” shaft friction design line was plotted against the mobilised shaft friction collated from the previous project – refer to black lines in Figure 5. It is noted that they represent a lower bound consistent with the definition of “characteristic” in Eurocode 7.

Table 1 presents the calculated embedment into OA per pile type following the requirements of Eurocode 7 for verification
of Design Approach 1, Combinations 1 and 2 (DA1-1, DA1-2).

In addition to the optimisation in pile length, the simplicity of the methodology allowed the verification process to be sped up, avoiding re-submissions of design to authorities. The methodology was satisfactory in terms of eliminating contractual risk for controlling embedment lengths during construction whilst still providing adequate factors of safety in compliance with Eurocode 7.

5 CONCLUSIONS AND FUTURE WORK

A discussion has been presented on the challenges faced by geotechnical practitioners at design stage to derive parameters for prediction of bored pile embedment lengths into residual soils, such as the Singapore Old Alluvium (OA).

A number of bored pile preliminary tests in the OA were collated and presented to assess the impact that the variability of the OA and construction methods can have on the final mobilised shaft friction measured during pile testing. Figure 4 shows that the majority of data plots within $f_s = (2$ to $3).N$, which is commonly adopted in Singapore practice. However, a larger overall variability from lower bound to upper bound (1N to 4N) was noted.

An alternative design approach using an overall assessment of the site based on SPT data was proposed for the selection of a characteristic N design line in accordance to Eurocode 7. A case study presenting the selected shaft friction parameters and the preliminary pile test results were discussed in terms of the advantages of the proposed methodology to minimise contractual/technical risk during construction whilst still providing an optimum design in terms total pile length installed.

Going forward, it is recommended to carry out further investigations into the effect of construction methods in bored pile design parameter. In collaboration with contractors, topics such as specifications and quality control of the support fluid, comparisons on the use of bentonite vs polymers, shaft and base grouting, effectiveness of base cleaning methods (e.g. air-lifting) could be investigated for the overall benefit of the project and the industry in Singapore.

6 REFERENCES


