Pile Capacity in Intermediate Geomaterials: A Comparative Study

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ABSTRACT
This comparative study is part of the reconstruction of a wharf near the Maritimes. One of the purposes of the project was to design deep foundations adapted to local conditions characterised by the presence of very dense sands and layers of indurated sand, also referred to as intermediate geomaterials (IGM). Indurated sands (IGM) make predicting bearing capacity and pile driving behaviour challenging especially with the limited data available on such soils. The aim of the study is to assess the bearing capacity and driving behaviour of piles in these soils, whose properties are similar to weak rock. Indurated soils present major challenges, notably the risk of premature refusal and exceeding the allowable steel stresses. The study evaluates the behaviour of open-ended and closed-ended piles (plugging effect) and analyses the performance of different types, diameters, and thicknesses to identify the option with the lowest risk for the project. Samples collected from nineteen boreholes were used to determine geotechnical properties through laboratory tests and data from the literature. The analysis for this study is based on: (a) Static methods according to MCIF (β and N_t approaches); (b) Numerical simulations using RSPile and GRLWEAP14 software; and (c) Identification of critical scenarios and stratigraphic variability. Capacity, penetration, and stress curves as a function of depth were superimposed for different behaviours to identify both the pile type most suitable for reducing driving risks and the most critical stratigraphic cases. The large number of stratigraphic models, pile types, and driving equipment available on the market results in a considerable volume of analyses, requiring a tailored methodological approach. The results showed that the pile capacity varies significantly with the pile type, the stratigraphy and the development of soil plug. Ultimately, this study highlights the challenges associated with indurated soils in terms of driving behaviour, as well as the risks of premature refusal and exceeding allowable steel stresses. It also demonstrates how these risks can be mitigated by analysing the behaviour of different pile types to optimise the final design. Furthermore, the study emphasises the importance of conducting full-scale pre-production load tests to confirm pile driving behaviour.

RÉSUMÉ
Cette étude comparative s'inscrit dans le cadre de la reconstruction d'un quai dans la région des maritimes. Une étude a été réalisée pour concevoir des fondations profondes adaptées aux conditions locales et particulières caractérisées par la présence des sables très denses et des couches de sable induré également appelées géomatériaux intermédiaires (IGM). Les sables indurés (IGM) rendre la prédiction des capacités portantes et le comportement au fonçage difficile. Le nombre de modèles stratigraphiques, types de pieux et d'équipement de fonçage disponible sur le marché implique le volume d'analyses considérable, nécessitant une approche méthodologique adaptée tout en considérant le peu de données disponibles sur ce type de sol. L'objectif de l'étude est d'évaluer la capacité portante et le comportement au fonçage des pieux dans ces sols dont les propriétés se rapprochent des rocs mous. Les sols indurés posent des défis majeurs, notamment le risque de refus prématuré et le dépassement des contraintes admissibles des aciers. L'étude vise à évaluer le comportement des pieux à bout ouvert et fermé (effet de bouchonnage) et analyse la performance de différents types, grosseurs et épaisseurs afin d'identifier celui présentant le moins de risque au projet. Les échantillons prélevés de dix-neuf ont été utilisés pour déterminer les propriétés géotechniques à l'aide des essais en laboratoire ainsi que les données dans la littérature. L'analyse pour cette étude repose sur : (a). La méthode statique selon le MCIF (approche β and Nt); (b) Des simulations numériques réalisées en utilisant logiciels RSPile et GRLWEAP14; et (c). L'identification des scénarios critiques et variabilités stratigraphiques. Des courbes de capacité, pénétration et contrainte en fonction de la profondeur ont été superposées selon des différents comportements afin d'identifier à la fois le type de pieux le plus propice à limiter les risques lors de l'enfoncement, mais également les cas stratigraphiques les plus critiques. En fin de compte, cette étude montre les enjeux liés aux sols indurés en termes de comportement au fonçage ainsi que les risques de refus prématuré et le dépassement des contraintes admissibles des aciers. Cette étude a également permis de minimiser ces risques en analysant le comportement de différents types de pieux pour optimiser la conception finale. En outre, l'étude montre l'importance de conduire des essais de chargement en préproduction en grandeur pour confirmer le comportement des pieux au fonçage.

1 INTRODUCTION

An intermediate Geomaterial (IGM) is a material that is transitional between soil and rock in terms of strength and compressibility (AASHTO 2024). Deep foundations installed in IGM present a significant challenge for geotechnical engineers. IGM formation processes fit into two basic categories: (a) soil has been strengthened to near rock-like characteristics, or (b) rock formations have been weakened to near soil-like levels (Mokwa and Brooks 2008). These materials may consist of clay-based (argillaceous) geomaterials, calcareous rocks, or very dense sand-based formations (O'Neill et al. 1996). Sand-derived geomaterials often exhibit high strength while maintaining a granular structure, which complicates their classification and the selection of appropriate bearing capacity design methods. Papageorgiou (1993) proposed that the analysis and design of piles installed in intermediate geomaterials should incorporate both a geological component, addressing the material's mode of formation, and a geotechnical component, focused on its engineering response. Under these conditions, conventional pile design methods—largely developed for either granular soils or rock—may lead to inaccurate predictions of bearing capacity or driving behaviour. This may result in an increased risk of premature refusal and exceeding the allowable stresses of steel casings.

This paper aims to contribute to improved design practices through a comparative study conducted on a port infrastructure project characterized by the presence of indurated sands exhibiting behaviour similar to IGMs.

2 SUBUSURFACE CONDITIONS AND IGM

2.1 Site Description

The site used in the current study is located within a port setting in eastern Québec and includes several wharves that will be reconstructed. The general stratigraphic profile consists of a surficial loose deposit of engineered fill overlying littoral marine sediments, underlain by bedrock composed of sandstone and siltstone.

From a geotechnical investigation program comprised of nineteen boreholes, a highly variable and complex stratigraphy was identified. The subsurface profile includes fill materials, loose marine sediments, sand deposits ranging from very loose to very dense, indurated sands, and deeper zones characterized by alternating layers of indurated soil and bedrock. Significant lateral variability in the elevation of these deposits was observed across the site.

2.2 Geotechnical Properties and Groundwater Conditions

According to the Unified Soil Classification System (USCS), the loose deposits consist mainly of sand and silt to silty sand (SM), and sandy silt containing trace to some clays (ML or ML–CL). These materials generally have typical unit weights ranging from 18 to 21 kN/m³, with typical effective friction angles between 28° and 38°, depending on their relative density and granulometry.

The indurated sands, on the other hand, are characterized by significantly higher mechanical properties. The material consists primarily of sand containing variable proportions of silt, ranging between 7.3% and 32.5%. According to the Unified Soil Classification System (USCS), these materials are predominantly classified as SM, with some instances of SP–SM.

Unconfined compressive strength tests performed on recovered samples indicate strengths typically ranging from 25.8 to 32.4 MPa. Measured unit weights for these materials vary between 22.8 and 24.8 kN/m³. An effective friction angle of approximately 40° was adopted for the analyses This value was estimated using the correlations proposed in the (The Canadian Geotechnical Society 2023). Except for stratigraphic variability, laboratory test results indicate limited variability in the mechanical properties of the indurated sands.

Groundwater conditions at the site are controlled by the marine environment, with the phreatic surface located approximately at mean sea level. All analyses were therefore conducted under fully saturated conditions, and vertical effective stresses were calculated assuming hydrostatic pore-water pressure distribution. This assumption directly influences the mobilization of shaft friction and tip resistance, particularly within the indurated sand layers where effective stress governs both strength and stiffness.

2.3 Classification of Intermediate Geomaterials

According to the FHWA-RD-95-172 report by O'Neill et al. (1996), intermediate soils can be grouped into three main categories as previously mentioned. The first two categories are considered cohesive materials and are defined by unconfined compressive strengths ranging from 0.5 to 5 MPa. The third category is predominantly granular and is typically associated with Standard Penetration Test (SPT) values between 50 and 100 blows per 0.3 m of penetration.

As part of the geotechnical investigation, a distinction was made between indurated soils and very dense soils based on their physical and mechanical properties, as well as on the encountered stratigraphic soil profile. Any layer in which refusal was encountered using a split-spoon sampler, and for which material recovery was still possible, was classified as indurated soil.

Borehole data generally show refusal conditions (SPT values greater than 100 blows per 0.3 m) within the fine sands, while double-tube diamond coring was required in the indurated soil layers. These results suggest that the fine sands would fall under the classification of very dense granular geomaterials, whereas the indurated sands exceed the bounds typically associated with this category of intermediate material.

Based on the classification framework proposed by Kulhawy et al. (1991), together with the results of unconfined compressive strength testing, the indurated sands would be more appropriately classified as moderately strong rock.

3 ANALYSIS METHOD

3.1 Stratigraphic profile by geostatistical methods

The variability in the stratigraphy across the site represents a major challenge for assessing pile capacity and driving behaviour. To better capture this variability and to identify potentially critical zones, a geostatistical estimation approach was applied using data from the boreholes completed as part of the site investigation. Figure 1 presents the borehole locations and the pile alignment under study.

The elevations of the sand and indurated sand layers were interpolated using a kriging method. This approach allows for the spatial distribution of these layers to be estimated while accounting for spatial correlation between boreholes and the uncertainty associated with the available data. Results from the geostatistical analysis highlight significant variability in both the elevation and thickness of the indurated sand layers across the site. Figure 2 represents the top elevation of the deposits interpolated using a kriging method.

Evaluating these results made it possible to define representative stratigraphic profiles and identify scenarios considered to be critical for use in the pile capacity and driveability analyses. This approach helps reduce the number of required design iterations by focusing on profiles that best capture the risk of premature refusal or excessive stress generation on steel components during pile driving.

Figure 3 presents the stratigraphic profile along the alignment of the proposed piles generated after implementing the geostatistical method.

Based on the stratigraphic profile and the elevation at which pile driving is expected to begin (-6.1 m), the most critical location was identified at approximately 50 m along the alignment. This location corresponds to the thinnest layer of loose deposits directly overlying the indurated sand. The stratigraphy at this location is hence selected for use in the comparative study.

3.2 Type of piles

The piles considered in the analyses include open-ended steel pipe piles with diameters and wall thicknesses of PP508 × 12.7 mm, PP610 × 19.05 mm, PP610 × 25.4 mm, and PP760 × 19.05 mm, as well as HP 350 × 152 sections. These pile sections were selected in advance based on the structural requirements of the project. A yield strength of 345 MPa was adopted for all pile types.

3.3 Plugging effect

The plugging in open-ended steel pipe piles has a significant influence on the mobilization of axial resistance and on pile driving behaviour. In sand deposits, full plugging is generally expected at a penetration depth-to-diameter ratio ranging from 25 to 35 (Paikowsky and Whitman 1990), which corresponds to depths of approximately 12.7 to 22.9 m for the sand layers encountered at the site. Because the occurrence of plugging and the depth at which full plugging develops are difficult to predict with certainty, the analyses were carried out considering both plugged and unplugged conditions.

3.4 Pile Design using Static Methods

The axial pile capacity was estimated using the β and N_t approaches from the fifth edition of the Canadian Foundation Engineering Manual (The Canadian Geotechnical Society 2023), taking into account vertical effective stresses and the mechanical properties of the indurated sands. These methods were applied conservatively, given their limited range of applicability when dealing with intermediate geomaterials (IGM).

In accordance with the recommendations of the CFEM (5th edition), β values of 0.3, 0.6, and 0.8 were adopted for loose, compact, and very dense soils, respectively. For the indurated sands, a β value of 1.0 (see Table 9.2 in CFEM 2023) and an N_t value of 120 (see Table 9.3 in CFEM 2023) were selected.

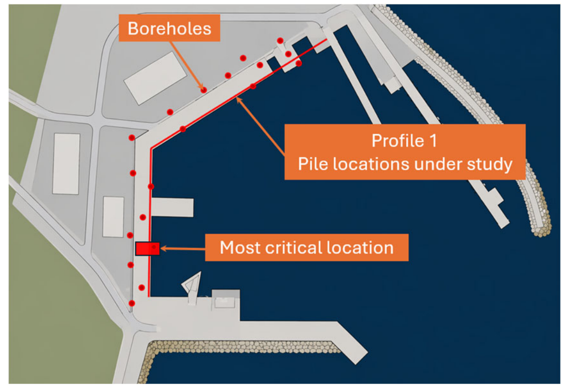

Figure 1. Borehole and pile locations

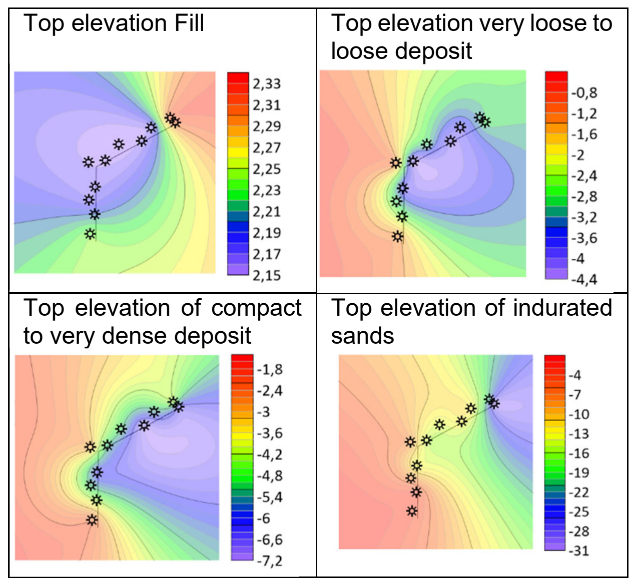

Figure 2. Variation in the top elevation of the main deposits encountered across the site

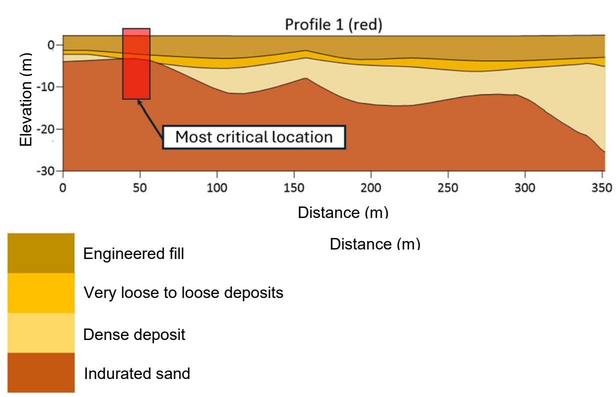

Figure 3. Stratigraphic profile of different deposits

3.5 Numerical Analysis

Numerical analyses were carried out using two software packages: (a) RSPile, version 3.030 by Rocscience; and (b) GRLWEAP14, version 14.1.20.1 by Pile Dynamics Inc. These programs were used to evaluate shaft and tip resistance, the plugging behaviour of open-ended steel pipe piles, pile driving performance, and the stresses induced in the steel for the different pile types selected for the study.

3.5.1 Numerical Analysis GRLWEAP14

The model was created from GRLWEAP14 software using the Soil Analysis (SA) method based on SPT-N values. However, instead of estimating parameters from SPT-N values, material properties were evaluated from laboratory data.

The unit shaft resistance in granular soil is compute using the following equation:

$$f_s = k_0 \tan\delta \sigma'_v \qquad [1]$$

Where

k_o = The earth pressure coefficient at rest;

δ = The pile-soil friction angle (degrees);

σ'_v = The vertical effective stress (kPa).

The concept of critical depth is not considered in the calculation; however, the value of fs is systematically limited to 250 kPa. It should be noted that there is a wide variation in limiting friction values and the internal friction angle. Some formulations based on Standard Penetration Test (SPT) values have been proposed to estimate the maximum value that may be considered (Meyerhof 1976). In the case of IGM with very high N-SPT values (refusal), this value is considered appropriate.

The unit toe resistance in granular is computed based on the uncorrected SPT N-value use following equation:

$$q_t = N_t \sigma'_v \qquad [2]$$

Where:

N_t = The toe bearing resistance coefficient according to (The Canadian Geotechnical Society 2023);

q_t = Ultimate tip or toe bearing resistance of the pile base area (kPa).

The concept of critical depth is not considered in the calculation; however, the value of q_t is systematically limited to 12,000 kPa for well graded gravel and unknown and poorly graded gravel, 20,000 kPa for sand and 30,000 kPa for gravel (Meyerhof 1976).

3.5.2 Numerical Analysis RSPile

The traditional Approach β and Nt was used to estimate the bearing capacity using the RSPile software. The geotechnical ultimate compressive resistance is obtained using the following equation:

$$R_u = \underbrace{\left(\sum_{z=0}^{L} C \times q_s \times \Delta z \right)}_{\text{shaft resistance}} + \underbrace{A_t \times q_t}_{\text{toe resistance}} \qquad [3]$$

Where:

$$q_s = \beta \times \sigma'_v \qquad [4]$$

Where :

R_u = Ultimate axial geotechnical resistance (kN);

L = Embedded length of the pile (m);

Δz = Subdivision increment of the pile embedment length (m).

C = External circumference of the pile (m);

q_s = Ultimate shear resistance along the shaft/Ultimate shaft Resistance (kPa);

β = A combined shaft resistance factor;

A_t = Base area of the pile tip (m²).

The concept of critical depth is applied by limiting the values of σ'_v and σ'_t.

3.5.3 Analysis of Pile Driving Behaviour

The behaviour of piles installed in IGMs remains poorly documented in the literature. Available case histories are limited and often specific to particular geological formations, which restricts the applicability of design parameters and highlights the need for load-test data to validate calculation assumptions.

At the preliminary design stage, the selection of appropriate pile types and installation equipment is critical to the overall success of the project. To support this process, pile driving performance analyses were conducted using the GRLWEAP14 software.

Although laboratory testing indicated limited variability in the mechanical properties of the indurated sands, it may exhibit variability in terms of composition, structure, and mechanical properties. This variability may influence both pile drivability and the interpretation of predicted driving resistance. To address this, the analyses were performed using representative ranges of input parameters derived from laboratory testing and available published data. For the indurated sands, three potential pile driving behaviours were considered:

- Sand-like behaviour, based on mechanical properties derived from laboratory test results. In this case, the sand layer has a thickness of about 3.1 m with a unit weight of 21 kN/m³ and a friction angle of 38 degrees. The indurated sand extends to the end of the model with m with a unit weight of about 22 kN/m³ and a friction angle of 40 degrees.
- Intermediate geomaterial (IGM)-type behaviour, using shaft friction (q_s) and tip resistance (q_t) values reported in the literature (Bin Masud et al. 2023). In this case a slightly higher value of 23 kN/m³ for the unit weight of the indurated sand was used. For the

q_s and q_t, two cases were modelled: one with average value of like materials, and the other with maximum values. The average values are 80 kPa and 9.6 MPa for the q_s and q_t, respectively, and the maximum values are 190 kPa and 12.49 MPa.

- Rock-like behaviour, with shaft resistance, q_s, values taken from the literature (Tran 2022) and tip resistance, q_t, derived from unconfined compressive strength test results obtained in the laboratory. The shaft resistance in the indurated sand layer was modelled using two rock-like behaviours, with lower- and upper-bound resistance profiles ("rock low" and "rock high"). These cases were defined using shaft resistance values reported by Tran (2022) for driven piles in weak rock with the high value of 500 kPa and the low value of 110 kPa, and tip resistance of 26 MPa derived from unconfined compressive strength test results, providing bounding scenarios for pile installation performance.

The term "refusal" may refer either to the geotechnical capacity of the pile or to installation limitations and must therefore be properly qualified. In this study, the termination criterion is defined in the context of drivability as the condition where the pile exhibits no measurable penetration, or where the hammer energy is insufficient to advance the pile, i.e. the maximum achievable penetration with the selected equipment. In GRLWEAP14, this condition is theoretically represented by an infinite blow count (9,999 blows). However, at high blow counts, results become highly sensitive to small variations in hammer energy. Accordingly, a practical refusal limit of 300 blows per metre (0.3 blow/mm) was adopted, consistent with GRLWEAP recommendations. Published criteria vary significantly depending on soil conditions and interpretation methods. For example, API RP 2A (API 2024) defines higher thresholds for both soft and hard soils, while Tomlinson and Woodward (2008) recommend limiting driving to approximately 120–150 blows per 250 mm to reduce the risk of damage. Other references suggest values ranging from approximately 1,000 to 1,250 blows per metre. As noted in AASHTO (2024), termination criteria based solely on blow counts remain dependent on soil conditions, pile type, hammer performance, and operational constraints. Based on these considerations, the following criteria were adopted for the analyses:

- termination at 300 blows per metre, representing practical refusal;
- A maximum induced pile stress of 276 MPa, corresponding to 80% of the steel yield strength,
- Achievement of the target axial capacity within the soil profile.

Finally, given the wide range of pile driving equipment available and the soil conditions encountered at the site, it was anticipated that a high-energy hammer would be required for pile installation. To limit the number of analysis iterations, all simulations were performed using a Bermingham B650S diesel hammer.

4 RESULTS

4.1 Axial Capacity of Pile

The results show a wide dispersion in the estimated pile driving depths depending on the used method The static design approaches tend to provide conservative estimates, with required pile lengths ranging from 10 to 23 m within the indurated sand layer (Figure 4). In contrast, analyses performed using RSPile indicate shorter pile lengths, ranging from 7.3 to 12.3 m (Figure 5).

For the GRLWEAP14 analyses, a much broader range of values was obtained, with estimated driving depths varying between 9 and 38 m (Figure 6). It should be noted that when modelling indurated sands as frictional-granular material in GRLWEAP14, the end bearing resistance is internally capped at 20 MPa. This limitation is related to the formulation of sand-type constitutive models rather than representing the actual mechanical strength of the material. As a result, end-bearing resistance may be underestimated at greater depths, leading to larger embedment lengths in some simulations. This modelling constraint partly explains the divergence observed between GRLWEAP14 and RSPile results.

4.2 Pile Driving Behaviour

Pile driving analyses were performed using the GRLWEAP14 software using the cases and criteria mentioned in section 3.5.3. The results presented in figures 7 to 9 indicate that soil plugging can significantly reduce the required embedment length to reach the capacity. The results also show that certain pile types present a high risk of exceeding allowable stress limits for steel, and that stratigraphic variability has a strong influence on the achievable depths before premature refusal occurs. From figure 7, the closed-ended piles reach the same ultimate capacity at lower embedment depth and the maximum compression stress generated in the steel are higher than the open-ended piles. Moreover, the number of blows per metre required to reach the same ultimate capacity for the same pile section are higher for closed-ended pipe piles than open-ended pipe piles, whereas for HP piles, both closed-ended and open-ended reached the termination criteria. The shaft resistance represents 77 % to over 90 % of the total resistance in open-ended piles, while it represents no more than 59 % in close-ended piles. The percentage is also directly proportional to the pile length.

In figure 8, it can be noticed that the required depth to get almost the same total resistance is greater than the double when using the average values of q_s and q_t for all type of piles showing the importance of shaft resistance is developing the total resistance especially in open ended piles where the shaft resistance represents more than 90%.

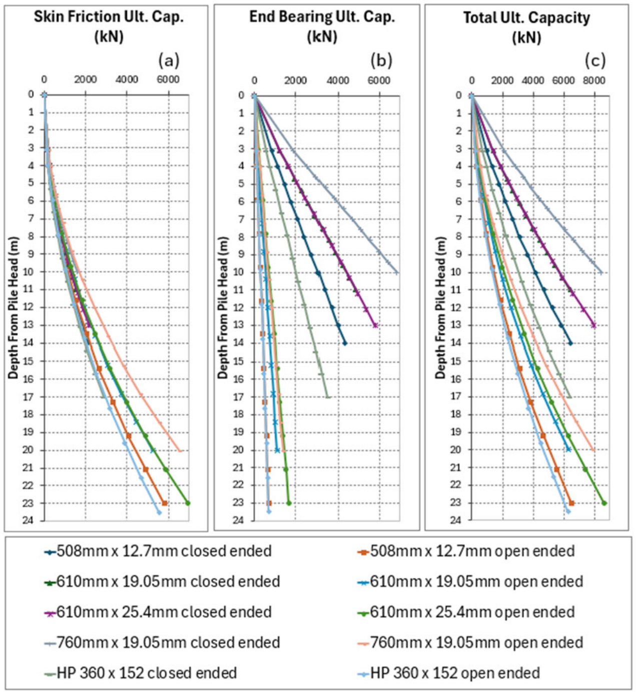

Figure 4. Results of Pile Capacity using Static Methods : (a) Skin Friction; (b) End Bearing; and (c) Total Capacity

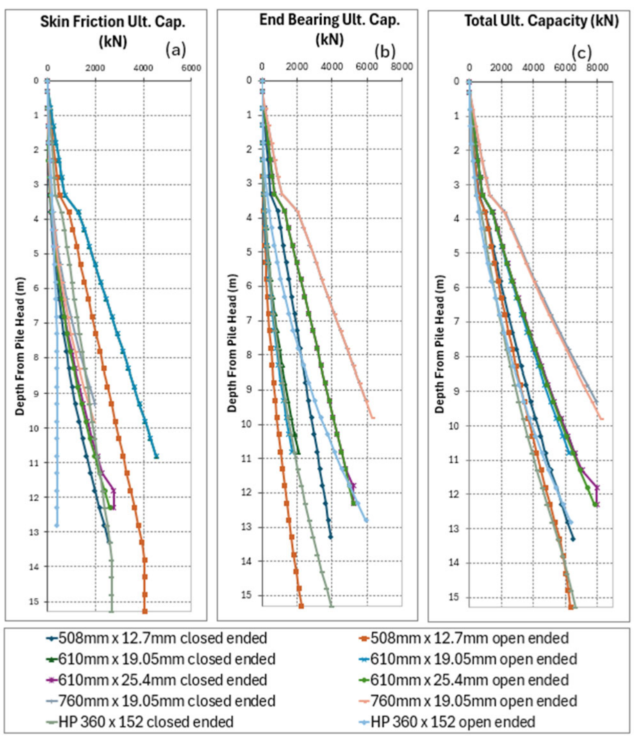

Figure 5. Results of Pile Capacity using RSPile Software : (a) Skin Friction; (b) End Bearing; and (c) Total Capacity

Moreover, in closed-ended piles, the risk to reach the termination criteria and or exceed the maximum allowable compression stress in steel is generally higher than open-ended-piles.

In figure 9, the assumed resistance level (low versus high shaft resistance values) of the indurated layer has a significant impact on predicted pile behaviour. For open-ended piles, adopting "rock-high" behaviour increases mobilised resistance by approximately 20 % to 50 % relative to "rock-low" assumptions, whereas the increase for closed-ended piles is typically limited to less than 10 % to 30 %. In contrast, the end condition itself exerts a much stronger influence: closed-ended behaviour results in resistance levels approximately 3 to 8 times higher than open-ended behaviour for the same pile size.

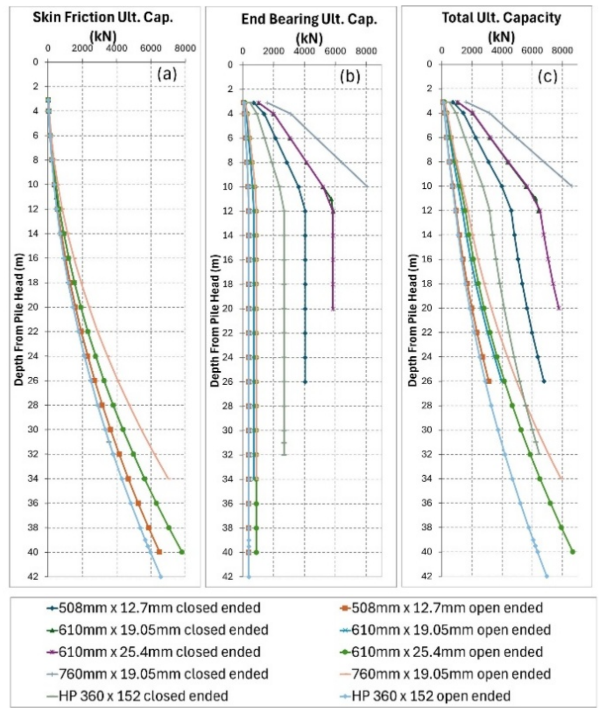

Figure 6. Results of Pile Capacity using GRLWEAP14 : (a) Skin Friction; (b) End Bearing; and (c) Total Capacity

For the pipe pile 610x25.4 open-ended, it can notice that using properties of the same materials published by Bin Masud (2023) to determine q_s and q_t led to two different depths to obtain almost the same ultimate capacity. Using the maximum values of the properties reduced the required depth to almost the half if using the average values. Whereas, determining properties from the results of laboratory tests result in a depth midway through those determined before. Using the low-rock assumption, the depth is nearly identical as using the results determined from the laboratory test. While using the rock-high assumption, the required depth is almost one-third of the low-rock assumption.

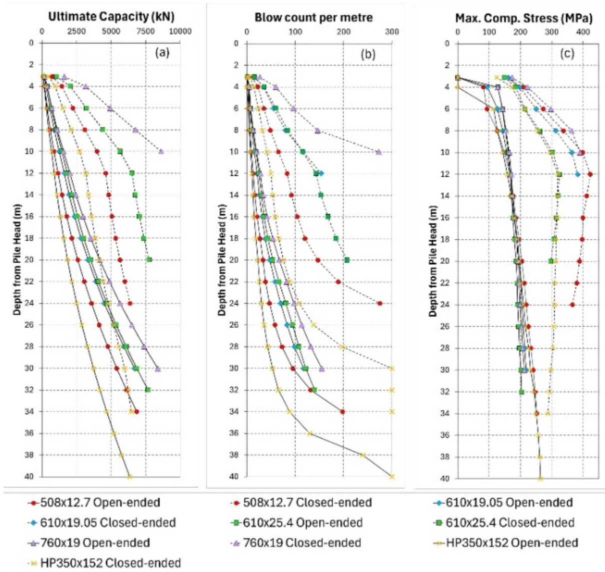

Figure 7. Results by GRLWEAP14 (a) Total Ultimate Pile Capacity; (b) Blow counts; and (c) Compression Stress in Steel versus depth using soil properties determined from laboratory testing

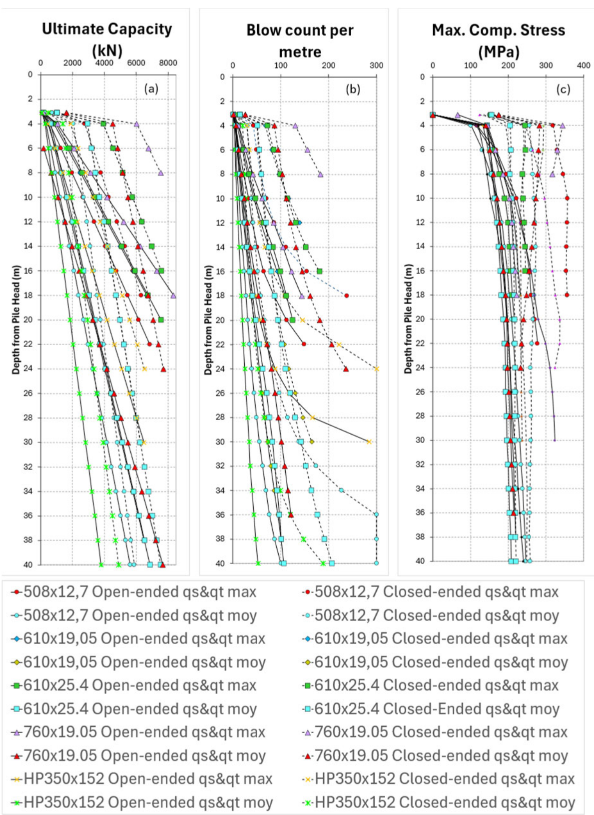

Figure 8. Results by GRLWEAP14 (a) Total Ultimate Pile Capacity; (b) Blow counts; and (c) Compression Stress in Steel versus depth using q_s et q_t as per Bin Masud et al. (2023)

4.3 Dynamic Loading Test

At the time of analysis, only one dynamic load test was carried out at the project site by others, located at a distance of approximately 75 m along the alignment. Based on the available information, the stratigraphy at this location appears generally similar to that of the critical stratigraphic profile used in the analysis, except that the indurated sand layer is encountered at a depth of approximately 30 m, whereas the test pile was driven to a depth of 10.1 m. As a result, this test does not allow for direct verification of pile driving behaviour within the indurated sand.

Nevertheless, back-analysis results indicate that the loose sands behave in accordance with their geotechnical properties using static design methods, while the compact to dense sands exhibit behaviour more consistent with IGMs. For these layers, shaft skin resistance, q_s, values were found to vary with depth from 300 to 1,120 kPa, with an average value of 710 kPa, and a tip resistance, q_t, of approximately 9,000 kPa. Moreover, these results support the assumption that soil plugging is likely to occur in dense deposits that behave as IGMs.

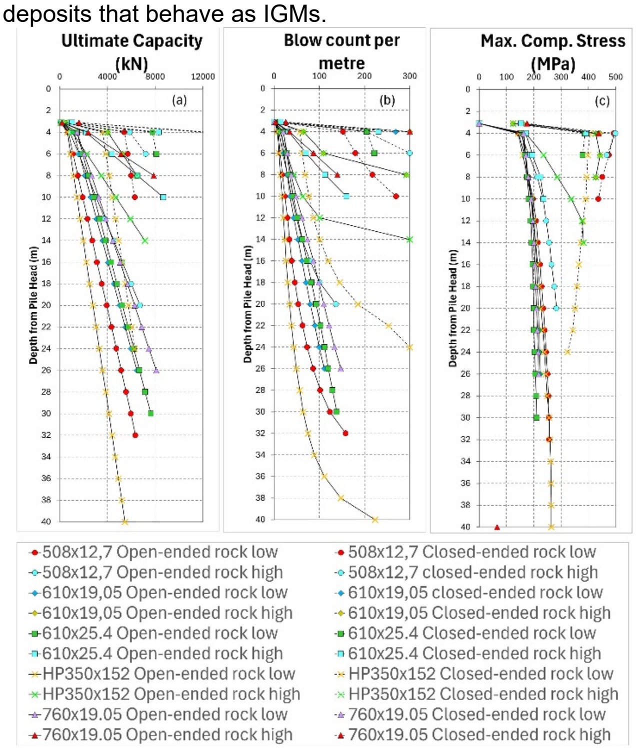

Figure 9. Results by GRLWEAP14 (a) Total Ultimate Pile Capacity; (b) Blow counts; and (c) Compression Stress in Steel versus depth using q_s as per Tran (2022) and qt determined from UCS obtained in the laboratory

5 DISCUSSION

The results highlight the limitations of conventional pile capacity estimation methods when applied to IGMs. Several parameters and modelling approaches were investigated as part of this analysis, including a range of mechanical properties and assumed behaviours for indurated sands based on values reported in the literature.

These aspects were examined for different pile diameters, wall thicknesses, and stratigraphic profiles.

The various analysis outputs generated using the GRLWEAP14 software made it possible to identify several potential risks associated with pile driving. These include challenges related to achieving the target axial capacity, the occurrence of premature refusal, and the exceedance of allowable stresses in the steel pile sections.

Although limited information is available in the literature regarding the actual behaviour of driven piles in indurated soils, the analyses performed suggest a direct relationship between pile plugging and the exceedance of stresses induced in the steel. When plugging occurs, resistance at the pile tip increases rapidly, leading to higher dynamic driving resistance and, consequently, elevated compressive stresses in the steel section. While plugging may reduce the required embedment to reach axial capacity, it simultaneously increases the risk of overstressing the pile during installation. Moreover, the driving depth could be significantly reduced if full or partial plugging were to occur.

Whereas indurated sands are commonly classified as intermediate geomaterials, their mechanical behaviour in pile driving can approach that of weak rock with shaft resistance and tip stresses comparable to values reported in the literature for rock materials. Under such conditions, on one hand, conventional soil-based design approaches may become inadequate, and resistance mobilization may be dominated by rock-like mechanisms. This transitional behaviour highlights the limitations of traditional classification systems and underlines the importance of combining laboratory data, numerical modelling, and full-scale testing to ensure safe and constructible foundation designs. On the other hand, limited penetration into the indurated sand is expected, along with a significant increase in the number of blows per metre required for pile driving. This behaviour could ultimately lead to induced stresses in the pile tube exceeding the allowable limits for the steel.

Although there was only one dynamic load test available at the site, its limited penetration depth did not allow for direct validation of pile behaviour within the indurated sand layer. While the test results support the validity of static design assumptions in loose to dense sands, they do not provide direct confirmation of shaft or tip resistance mobilization in the indurated horizon. Consequently, uncertainty remains regarding pile behaviour in these materials, reinforcing the need for full-scale pre-production testing.

Finally, the analyses indicate that piles with smaller diameters and greater wall thicknesses provide more favourable installation conditions. In the present case, a 610 mm × 25.4 mm steel pipe pile was identified as the most suitable option for minimizing both the risk of premature refusal and the likelihood of exceeding the specified maximum steel stresses.

6 RECOMMENDATIONS AND CONCLUSIONS

This study highlights the challenges associated with the design of piles installed in intermediate geomaterials. The main conclusions can be summarized as follows:

- Intermediate geomaterials require a specific design approach, distinct from that used for conventional granular soils. A conservative design approach is particularly taken up for piles driven into indurated sands.
- Pile plugging plays a key role in both axial bearing capacity and driving behaviour. While a conservative assumption is preferable at the design stage, dynamic load testing suggests that plug formation is likely to occur in intermediate geomaterials.
- Full-scale pre-production pile load tests are essential to validate design assumptions and reduce uncertainty, especially in indurated sands where little to no load test data are currently available.

The analysis results presented in this paper contribute to a better understanding of the possible behaviour of piles driven into indurated sands and provide practical guidance for reducing the risk of premature refusal or excessive stresses induced in the steel during pile driving.

Although indurated sands are expected to exhibit pile driving behaviour similar to that of rock, dynamic load testing is recommended to confirm this behaviour and support final design decisions.

7 REFERENCES

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