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Prospects on data mining approach for pile geotechnical design utilizing CPT and CPTu records: Case study: AUT database

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ABSTRACT: A comprehensive database has been compiled including CPT soundings performed adjacent to pile load test and related geotechnical information, namely AUT (Amirkabir University of Technology): Geo-CPT&Pile Database. In this paper, after a brief review of existing CPT and pile databases, the specifications of the updated AUT: Geo-CPT&Pile Database as well as different categories of data are presented. Subsequently, several procedures developed using this database from different geotechnical aspects are reviewed and introduced. These implementations are extended for appraisal of currently used CPT-based methods for pile geotechnical design by focusing on methods screening, uncertainty- reliability measures, and Performance-Based Design (PBD) approach regarding resistance factors. After all, an algorithm is presented including a formulated procedure of pile geotechnical design by means of smart database collections, reproduction of CPT profile, assortment of competitive methods, integration of geotechnical aspects i.e., capacity, load-displacement performance and resistance distribution. Correspondingly, via realizing prospects on implementation of major aspects leads towards optimum pile performance-based design upon a data mining approach.

1 BACKGROUNDS

The application of databases in geotechnical engineering returns to long decades ago since researchers tried to develop correlations among in-situ or lab measured parameters and design geotechnical parameters. Cone penetration testing (CPT) is one of reliable in-situ testing with less measurement error in comparison to others (Phoon and Kulhawy 1999). It provides continuous records with depth and due to its similarity to piles, a broad range of correlations have been made for prediction of ultimate pile bearing capacity (Eslami and Fellenius 1997). Piles are important foundation systems in geotechnical engineering facilitating construction in offshore and onshore areas or even in abnormal subsoil conditions or extreme loads imposed by superstructure in high-rise buildings and skyscrapers.

CPT-based methods differ in many areas such as the compiled CPT and pile database regarding the pile characteristics and the subsoil conditions where these piles were installed, model assumptions and simplifications, input parameters for predicting unite side and toe resistances, data processing for excess pore water pressure in back shoulder of CPT cone, failure pattern around the pile toe and so on. For instance, some methods consider loading directions or friction fatigue in their correlations while others do not, or some methods have been develop based on total stress analysis (TSA) while some were developed based on effective stress analysis (ESA) or empirical correlations. Accordingly, various assessment criteria have been introduced to measure accuracy, precision and efficiency of these predictive methods (Eslami et al. 2019a).

The application of CPT and pile databases cannot be limited to performance assessment of predictive methods and these databases can provide us with more information.

Present study introduces a comprehensive geotechnical engineering database in the field of CPT and pile. This database named as AUT:Geo-CPT&Pile database has had different applications in the pile engineering such as reliability-based assessment of drilled displacement piles (Moshfeghi & Eslami 2019), assessing the performance of CPT-based methods in predicting axial bearing capacity of helical piles, reproduction and realization of CPT records (Jamshidi Chenari et al. 2018), predicting the load displacement behavior of driven piles regarding CPT records, and uncertainty appraisal of CPT-based methods regarding statistical, probabilistic and reliability-based criteria (Eslami et al. 2020, Heidarie Golafzani & Eslami 2021) and the

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importance of relevant data-based approach in geotechnical pile design (Eslami & Heidarie Golafzani 2020). Eventual1y, a CPT and pile data-based approach is introduced for pile design regarding the researches have been done.

2 AUT: GEO-CPT&PILE DATABASE; AN EFFICIENT TOOL IN DATA MINING FOR GEOTECHNICAL PILE DESIGN

The AUT:Geo-CPT&Pile database has been compiled from well-published and documented geotechnical engineering sources and includes 600 records of pile loading tests along with the results of adjacent cone or piezocone penetration tests (Moshfeghi et al. 2015; Eslami et al. 2019b).

This database was primarily aimed to assess the performance of different CPT-based methods. Moshfeghi & Eslami (2018, 2019) compiled a database of fourty-three and seventy-six records of driven piles installed in sandy soils and their adjacent CPT records from AUT:Geo-CPT&Pile database and studied the effect of different criteria for interpretating static pile load test records to select the most consistent approach with the CPT-based methods. Among the four selected criteria, the Brinch Hansen 80% criterion and the load at the displacement of 10% of the pile diameter were the two most consistent criteria with the CPT-based approaches. They also assessed the performance of different CPT-based methods considering wasted capacity index (WCI) and cost optimization regarding safety factor. Assessments indicate that the German (Kempfert & Becker 2010), LCPC (Bustamante & Gianeselli 1982), Meyerhof (1983), UniCone (Eslami & Fellenius 1997) and UWA-05 (Lehane et al. 2005) methods have shown the most efficient predictions at their optimum factor of safety.

Askari Fateh et al. assessed the performance of ten direct CPT-based methods for helical piles via considering thirty-seven cases of helical piles installed in different soil types. Also, the accuracy of two different assumptions of failure mechanism around helical piles was examined through comparing the predicted axial bearing capacity and measured ones in static pile load tests. Finally, they suggested a new CPT-based method to estimate the bearing capacity of helical piles (Eslami et al. 2019a).

Jamshidi et al. (2018) developed an algorithm for realization of CPT data based on non-stationary random field theory. The proposed algorithm imposes soil layering alongside inherent soil variability based on Eslami and Fellenius (1997) soil classification chart. After detection of soil layering based on the simplified proposed approach, the statistical characteristics of each soil layer are defined as multi-criteria functions, assembled into the non-stationary autocovariance matrix and the routines continue in Monte Carlo scheme for production of CPT records.

Valikhah et al. proposed a new analytical-numerical method to estimate axial load-displacement behaviour of driven piles in granular soils using CPT records. Implementing the method of stress characteristics, they analysed the stress field below and around the pile and in effect, the failure mechanism. This failure mechanism has then been used by implementation of the kinematical approach of the limit analysis to compute the displacement field (Eslami et al. 2019a).

The application of artificial intelligence has been developed in geotechnical engineering in recent years. Implementing group method of data handling type neural networks optimized using genetic algorithms, Ardalan et al. (2009) estimated the pile unit shaft resistance.

Eslami et al. (2020b) by employing a database of instrumented pile load tests as well as CPT records correlated the pile unit shaft resistance with CPT sleeve friction. They proposed an analytical-empirical procedure for estimating pile shaft capacity considering scale effects. Factors such as mechanism and rate of penetration, size effect (i.e., length and diameter), friction fatigue are taken into account in this approach.

Heidarie Golafzani et al. (2020a, b) compiled a database of sixty driven piles installed in different soil types and studied the performance of different approaches, i.e., static analyses, SPT-based methods and CPT-based methods including twelve methods. In their studies, they considered different statistical, probabilistic and reliability-based criteria, including mean and coefficient of variation, best fitted line, 20% accuracy level, cumulative distribution function (i.e., P_{50} and P_{90}-P_{50}), confidence interval, root mean square error (RMSE) and efficiency ratio (i.e., the ratio of load and resistance factor (LRFD) resistance factor to the model parameter). The model parameter was defined as the ratio of measured to predicted bearing capacity. They concluded that modified first order second moment (FOSM) is less time-consuming and complicated, and leads to statistically identical resistance factors to first order reliability (FORM) method and Monte Carlo simulations (MCS). They also compared the performance of the considered approaches and methods via radar charts and deduced that CPT-based methods perform better than two other approaches.

Eslami & Heidarie Golafzani (2020) stated that selection of predictive methods for pile geotechnical design has a pivotal role in an optimum and site-specific design. Results indicated that methods prioritized by statistical, probabilistic and reliability-based criteria attain higher resistance factor in load and resistance factor design (LRFD) or lower safety factor in allowable stress design (ASD) approaches. They emphasized that the global safety factor cannot stands alone against all uncertainty sources and methods attaining similar safety factors, do not result in the same probability of failure and reliability index (i.e., β).

3 GEOTECHNICAL DATA-BASED PILE DESIGN

As reviewed, CPT and pile databases support the geotechnical designer with invaluable information about the performance of predictive methods for special pile types installed in a particular project site/with definite characterizations or even for a wide range of pile types installed in various site locations and conditions. Furthermore, databases can be mined for extra information aiding in geotechnical pile design. Figure 1 illustrates the steps for this new suggested/proposed approach.

In this approach, it is necessary to compile a database of geotechnical information about various sites including pile load test results along with adjacent CPT records to the investigated piles.

In the first step, the engineer should evaluate the site conditions in terms of its available geotechnical information and categorizes it as no testing, minimum number of testing and comprehensive geotechnical site investigation.

If the number of tests is minimum or tests are unavailable, it is referred to the database for either gaining extra information via smart selection according to the available akin sites or data production generally such as CPT data or specifically such as P-Δ and resistance distribution if necessary. These procedures constitute the first stage of data collection.

The second stage is about processing the axial pile bearing capacity predictions. Various methods and approaches result in a wide range of predictions. Regardingly, applying miscellaneous evaluation criteria including statistical and probabilistic criteria and risk, reliability and efficiency-based criteria, leads to selection of appropriate methods according to the available site conditions, codes and local information. Indeed, this stage is dedicated to method screening leading to optimum geotechnical design. Eventually,

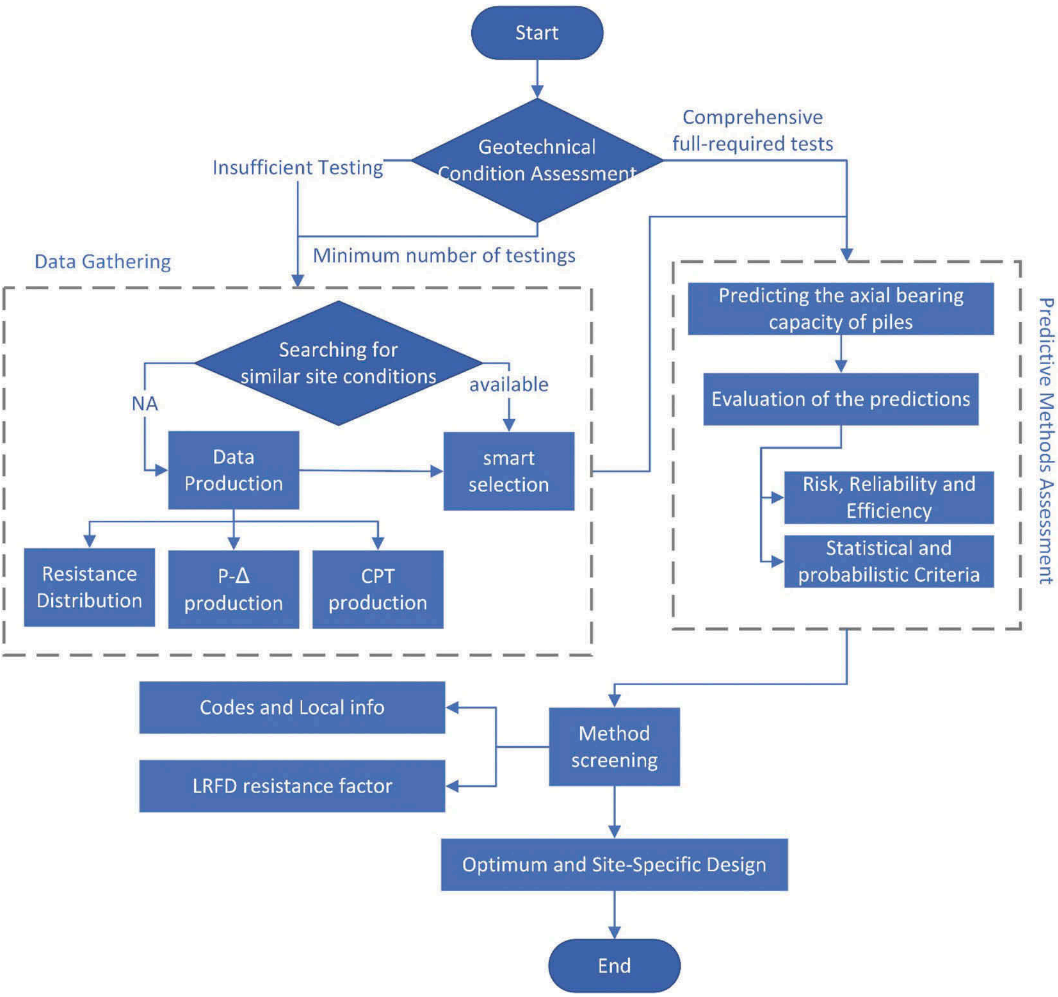


Figure 1. Geotechnical data-based pile design algorithm.

the understanding of the geotechnical engineer is improved and an optimum site-specific design approach is attained.

4 ENGINEERING IMPLEMENTATION

A database of sixty driven piles was gathered from the AUT:Geo-CPT&Pile database with their adjacent CPT records worldwide to illustrate the application of the proposed data-based geotechnical pile design approach. Most of the piles are installed in clayey soils (i.e., about 45% of the piles in the compiled database), followed by sandy soils (i.e., about 32%) and mixed soils (I.e., about 23%). According to what explained in the earlier section, for an optimum geotechnical pile design, it is appropriate to perform a comprehensive in-situ and lab tests to characterize the subsoil conditions and further consider it. In the case, the number of tests was limited or was not available for the current project, the geotechnical practitioner can gather extra information about the project site by searching through the available geotechnical site investigation reports for the nearby projects or a by smart selection from CPT and pile databases.

From the investigated database a driven pile was selected. This circular concrete pile was installed in sandy soils of Norway with embedment length of 15.5 m and diameter of 280 mm. By searching for similar site and pile conditions, a concrete square pile installed in Sweden was selected with embedment length of 12.8 m and width of 235 mm. Figure 2 provides the soil behavior classification (SBC) for these two close sites. As it is presented, the most majority of soil types are silt-sand and sand-gravel regarding the Eslami and Fellenius (1997) soil behavior classification.

Figure 3 illustrates the static pile load test (PLT) results for these two piles. Both piles behaved similarly under compression loading. As stated earlier, in case insufficient geotechnical data, Jamshidi Chenari et al. (2018) proposed a non-stationary algorithm for reproduction and realization of CPT records regarding soil stratigraphy.

Figure 4 compares the reproduced CPT records, i.e., q_c and f_s and their analogous real ones for the two investigated sites in Norway and Sweden. The geotechnical engineer can reproduce these CPT records with different inherent soil variability changing from low to high in soil characteristics reflecting the subsoil condition.

Figure 5 compares the performance of different CPT-based methods for these two piles via model parameter and it is the ratio of measured to predicted bearing capacity, i.e., Q_m/Q_p. The site conditions for these two considered piles, influence the performance of predictive methods appropriately in a similar way. For instance, if the acceptable limit for Q_m/Q_p changes from 0.8 to 1.2 as is shown in Figure 5, methods such as LCPC (Bustamante and Gianesselli

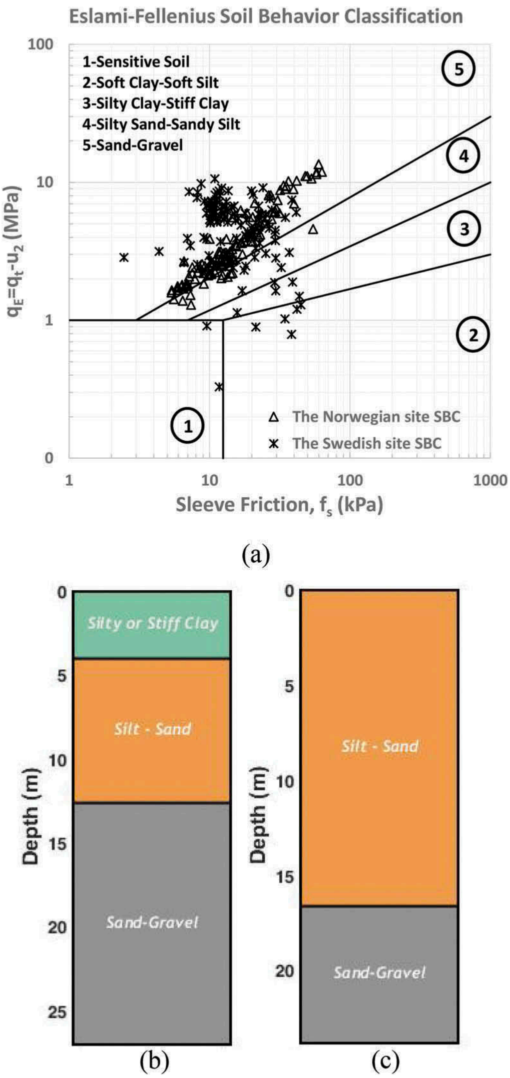


Figure 2. Soil stratigraphy; (a) soil behavior classification for the two sites (Eslami and Fellenius 1997), (b) the subsoil layering in Sweden, (c) the subsoil layering in Norway.

1983), Meyerhof (1983), UniCone (Eslami and Fellenius 1997), German (Kempfert and Becker 2010), and Modified UniCone (Niazi and Mayne 2016) have led to close predictions. However, other investigated methods, including Schmertmann (1978), Dutch (de Ruiter and Beringen 1979) andFugro-05 (Kolk et al. 2005) resulted in less accurate predictions due to the differences mentioned earlier. Regardingly, finding matching piles with similar dimensions and embedment length installed in close or near close site conditions, enhances the geotechnical engineer to have an optimum site-specific design by selecting appropriate criteria and implementing multi-criteria decision-making models.

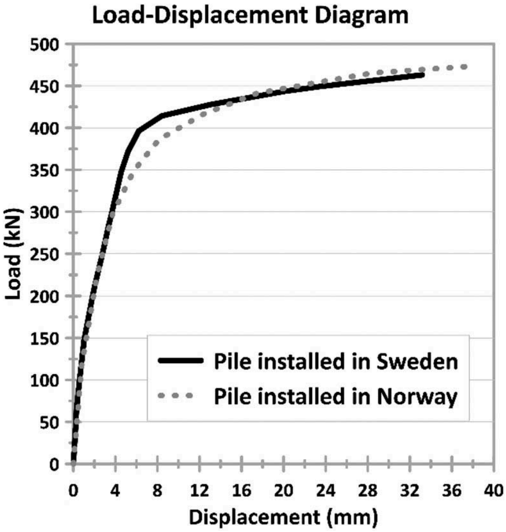
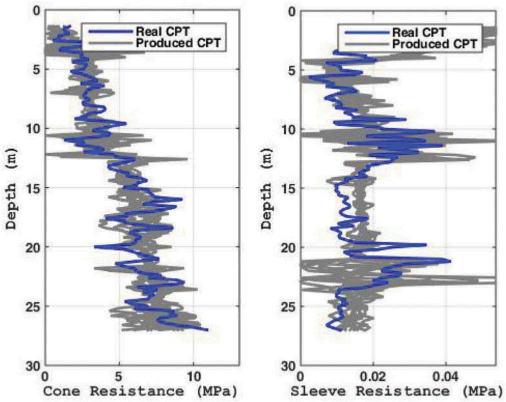
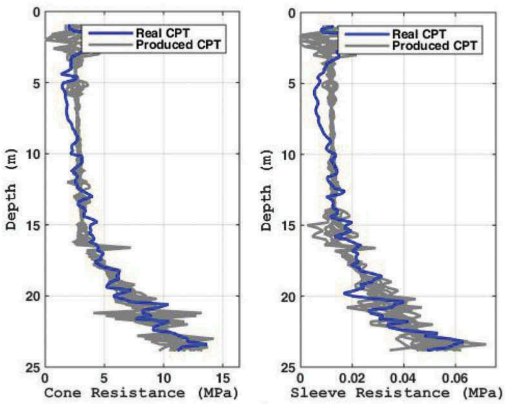


Figure 3. Pile load test results for the two considered piles.



(a)



(b)

Figure 4. Reproduced CPT records for the two site conditions, (a) the Swedish site, (b) the Norwegian site.

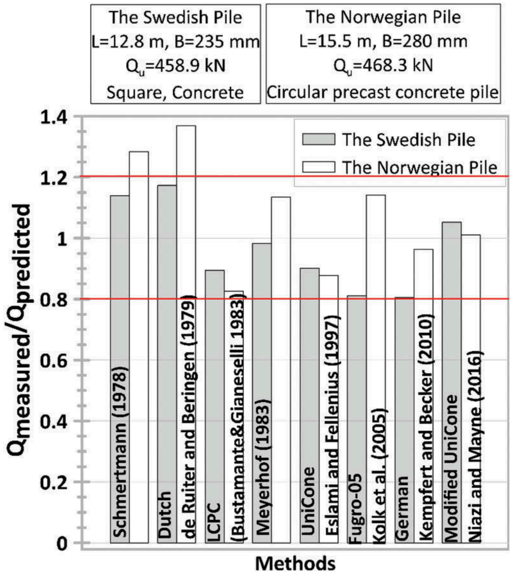


Figure 5. The performance of different CPT-based methods for these two considered piles.

5 CONCLUSIONS

Uncertainties are an inseparable part of geotechnical engineering, and many attempts have been made to consider their influence on geotechnical designs in the last decades. Characterizing the subsoil conditions is one of the essential steps in geotechnical designs, and CPT by producing continuous and reliable records has a crucial role in determining inherent soil variability. One of the primary applications of CPT soundings is predicting axial pile bearing capacity due to its similarity to the pile. In this regard, several methods have been developed based on CPT records. However, these methods result in a wide range of predictions according to the embedded uncertainties. To overcome the difficulties of selecting an appropriate predictive method, CPT and pile databases assist the geotechnical engineer. Accordingly, AUT:Geo-CPT&Pile database was introduced, and its implementation in various pile engineering issues was reviewed. However, the data mining of such a database is not limited to performance assessment of predictive methods, and an algorithm for data-based pile design approach is its other prospect. In this approach, with the aid of available data in the compiled database, the designer can search for the matching site and pile conditions in the absence of necessary and sufficient site geotechnical information or even reproduce and realize CPT records. After gathering adequate CPT and pile data, various predictive methods can be assessed via statistical, probabilistic, and reliability-based criteria. Eventually, the methods' screening procedure is finalized via considering codes and local info, and the superior methods are selected. Correspondingly, the final pile geotechnical design will be an optimum pile performance-based design upon a data mining approach. The Application of this algorithm was presented through an example.

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