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# Axial Load Capacity Prediction of Single Piles in Clay and Sand Layers Using Nonlinear Load Transfer Curves

## 비선형 하중전이법에 의한 점토 및 모래층에서 파일의 지지력 예측

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**ABSTRACT :** The present study has extended OpenSees, which is an open-source software framework DOS program for developing applications to idealize geotechnical and structural problems, for the static analysis of axial load capacity and settlement of single piles in MS Windows environment. The Windows version of OpenSees as improved by this study has enhanced the DOS version from a general purpose software program to a special purpose program for driven and bored pile analysis with additional features of pre-processing and post-processing and a user friendly graphical interface. The method used in the load capacity analysis is the numerical methods based on load transfer functions combined with finite elements. The use of empirical nonlinear T-z and Q-z load transfer curves to model soil-pile interaction in skin friction and end bearing, respectively, has been shown to capture the nonlinear soil-pile response under settlement due to load. Validation studies have shown the static load capacity and settlement predictions implemented in this study are in fair agreement with reference data from the static loading tests.

**Keywords :** Static axial load capacity, Settlement, Piles, Shafts, Soil-pile interaction, Nonlinear load-transfer curves

**요 지 :** 본 연구에서는 지반 및 구조물의 문제점을 이상화 하는데 필요한 응용기술을 개발하기 위해 공개되어 있는 소프트웨어 즉 도스용OpenSees프로그램을 윈도우상에서 말뚝의 정적 지지력과 침하를 분석할 수 있도록 하여 윈도우상에서 사용자가 편리하게 전 처리와 후 처리 및 경계조건 처리가 가능하도록 OpenSees프로그램을 개선하였다. 본 연구에 사용된 지지력 분석은 유한요소해석과 합성된 하중전이함수에 근거한 수치해석방법이다. 본 연구에서는 흙-말뚝의 상호작용에 의한 마찰력과 선단 지지력을 각각 모델링하기 위해 경험적인 비선형 T-z과 Q-z곡선에 의한 하중전이법을 이용하여 하중재하에 따른 침하조건에서의 흙-말뚝의 반응을 나타내었다. 본 연구에서 예측한 정적 지지력과 침하량은 문헌에 의한 정적재하시험 결과와 잘 일치하는 것으로 나타나 유용하게 활용될 수 있을 것으로 판단된다.

**주요어 :** 정적 지지력, 침하, 항타말뚝, 매입말뚝, 흙-말뚝 상호작용, 비선형 하중전이곡선

## 1. Introduction

The determination of the ultimate load capacity and settlement of deep foundations has been a primary concern of the geotechnical engineers, and various inexpensive methods have been adopted for the analysis of capacity and settlement evaluation because pile load tests are complicated and expensive. A typical means of capacity and settlement evaluation of deep foundations is through analytical and numerical prediction with the use of finite element analysis when given a reliable soil property data from soil tests and boring logs at the site. A practical alternative to capacity simulation and analytical prediction is the open-source software development tools that engineers could freely download and use, such as OpenSees (Open System for Earthquake Engineering Simulation) developed at University of California, Berkeley. OpenSees (2000) is a software framework for developing applications to simulate the performance of structural and geotechnical systems using finite element methods with the goal to improve the modeling and computational simulation through open-source development. The current version is in DOS (Disk Operating System) based platform with no preprocessing and post processing features. The present study has made enhancements to the current version from being a general purpose structural and geotechnical DOS software program to a special purpose MicroSoft

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Windows program, by providing a graphical user interface (GUI) and pre/post-processor, for the specific application of predicting the ultimate static axial load capacity and settlement of single piles and shafts using nonlinear load transfer curves to model soil-pile skin friction and end-bearing resistances. The load transfer method has been successfully applied to the analysis of piles under external load (Seed and Reese, 1957; Kezdi, 1960; Reese, 1964; Coyle and Reese, 1966; Reese et al., 1969) where it appears to be a simple and flexible method. Results of pile load capacity and settlement predictions by the program are then validated and compared with reference data of in-situ static load tests on piles and shafts.

## 2. Analysis of Axial Load Capacity and Settlement of Single Piles and Shafts

The total ultimate load-carrying capacity $Q_u$ of a pile or shaft is given by the equation;

$$Q_u = q_u A_p + \sum(f_s\, p\, \Delta L) \quad (1)$$

where $q_u$ is the unit ultimate end bearing capacity of the soil at the level of the pile tip, $A_p$ is the area of the pile tip, $f_s$ is the unit ultimate frictional resistance or soil-pile adhesion strength, and p is the pile perimeter at any segment $\Delta$L. The term $q_u.A_p$ is the total load capacity in end-bearing and the term $\Sigma(f_s.p.\Delta L)$ is the total load capacity contributed by the pile/shaft side shear calculated by the summation of the side shear forces along the pile's embedment length.

Numerous published studies cover the determination of $q_u$ and $f_s$ for single piles and drilled shafts and an excellent summary has been provided by Das (2004) and Poulos (1989). In this study, the evaluation of $q_u$ and $f_s$ for driven piles and drilled shafts are formulated based on the United States Federal Highway Administration (FHWA) specifications for Design and Construction of Driven Pile Foundations (Hannigan et al., 1998) and Drilled Shafts Construction Procedures and Design Methods (O'Neill and Reese, 1999).

With the advent of computers, many effective methods of analysis have been developed to predict the settlement and load distribution of deep foundations. The method used in the program analysis is the numerical methods based on load transfer functions combined with finite elements, which are appropriate for use in analyzing piles and drilled shafts in layered soil profiles and in cases where settlement can potentially control the design (O'Neill and Reese, 1999). A one-dimensional (1D) soil-pile model is used following the method presented by Brandenberg (2004) and Kim et al. (2007) that involves modeling the pile as a series of elements supported by discrete nonlinear vertical springs at the ends of each pile segment, which represent the resistance of the soil in skin friction, called T-z springs, and a nonlinear spring at the pile tip representing the end-bearing resistance of the soil, called Q-z spring (Fig. 1). The stiffness of the springs is defined by normalized nonlinear load-transfer curves for skin-friction and end-bearing (Fig. 2) representing the respective load-displacement relation of the soil-pile resistances and relating the ratio of the load transfer to the pile movement. Such curves were developed for soils as clay and sand from results of a database of field and laboratory loading tests from the literature, which were implemented in OpenSees.

The ultimate end-bearing resistance $Q_u$ of the Q-z spring material is given by the first term in Eq. (1). The ultimate skin-friction resistances $T_u$ of the T-z spring materials were calculated based on adhesion strength for cohesive materials (clay), and based on frictional strength for cohesionless materials (sand) (Brandenberg, 2004) for any tributary length of segment

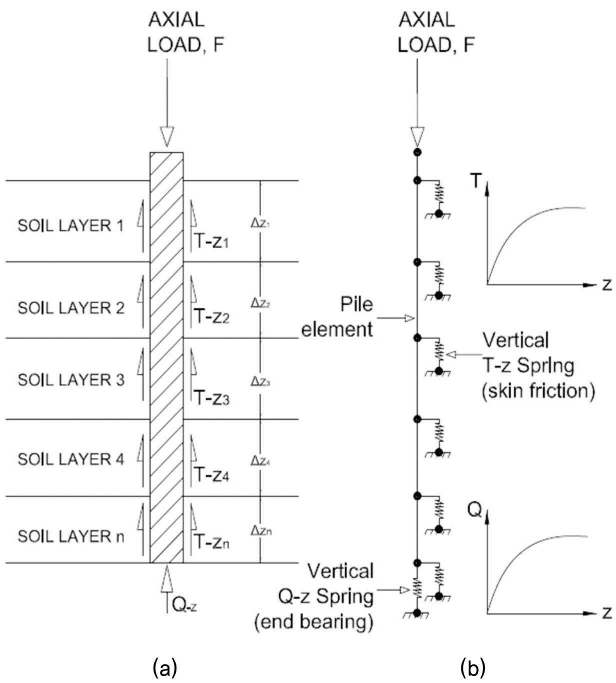



Fig. 1. A one-dimensional (1D) soil-pile model: (a) soil-pile profile, (b) soil-pile model using nonlinear load transfer curves in skin friction and end bearing.

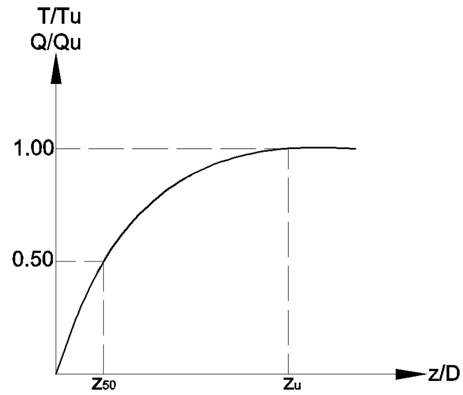



Fig. 2. Typical normalized nonlinear load transfer curve.

$\Delta L$ and perimeter p. The relative displacement when the ultimate skin friction resistance $T_u$ is first mobilized is calculated as 0.5% of the pile diameter or width (Boulanger, 2003a). The $z_{50}$ value (Fig. 2) is the displacement as a fraction of the pile diameter at which 50% of the ultimate load resistance at the pile-soil layer is mobilized (Mazzoni et al., 2006).

For clay,

$$T = f_s \ p \ \Delta L \tag{2}$$

where $f_s$ is the soil-pile adhesion strength evaluated from total stress approach as a fraction of the undrained shear strength ($\alpha$-method).

For sand,

$$T = K_o \ \sigma_v^{'} \ \tan\delta \ p \ \Delta L \tag{3}$$

where $K_o$ is the coefficient of active pressure at rest, $\sigma'_v$ is the vertical effective stress, and $\delta$ is the soil-pile friction angle.

## 3. One-dimensional Soil-pile Analysis Using Nonlinear T-z and Q-z Curves: Program Algorithm Development

The computer program OpenSees ALPile (Axially Loaded Pile) in MS Windows is an enhancement of the general purpose DOS program OpenSees (2000) to a special purpose program for driven and bored pile analysis with additional features of pre-processing and post-processing and a user friendly graphical interface. It relieves the user of any required programming skills for creating the required input and processing of the output data for the pile and soil modeling,

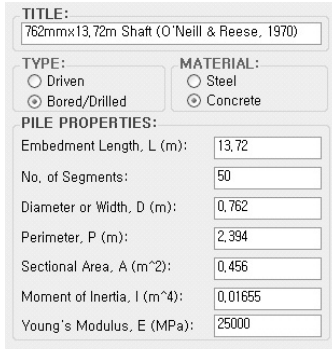
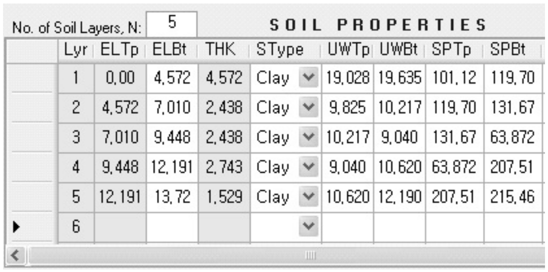



Fig. 3. Pile properties input.



No. of Soil Layers, N: 5 — SOIL PROPERTIES

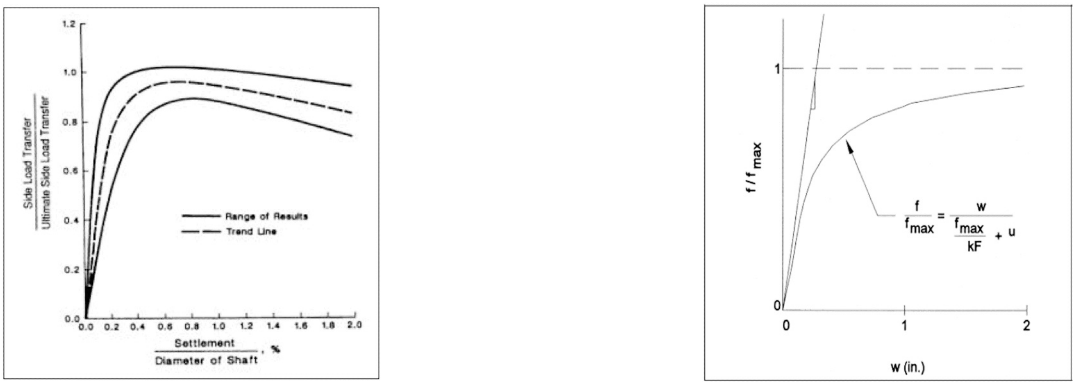
| Lyr | ELTp | ELBt | THK | SType | UWTp | UWBt | SPTp | SPBt |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.00 | 4.572 | 4.572 | Clay | 19.028 | 19.635 | 101.12 | 119.70 |
| 2 | 4.572 | 7.010 | 2.438 | Clay | 9.825 | 10.217 | 119.70 | 131.67 |
| 3 | 7.010 | 9.448 | 2.438 | Clay | 10.217 | 9.040 | 131.67 | 63.872 |
| 4 | 9.448 | 12.191 | 2.743 | Clay | 9.040 | 10.620 | 63.872 | 207.51 |
| 5 | 12.191 | 13.72 | 1.529 | Clay | 10.620 | 12.190 | 207.51 | 215.46 |
| 6 | | | | | | | | |

Fig. 4. Soil properties input.

analysis, and axial load capacity and settlement prediction of single piles and shafts. It basically integrates the input and output generation in one graphical user interface (GUI) and thereby making it friendly to use.

OpenSees ALPile accepts basic input data of the elastic pile properties (Fig. 3), the nonlinear properties of the soil at the different layers (Fig. 4), and the applied axial load and basically writes the required input data files and analysis parameters in Tcl file format (www.tcl.tk) that OpenSees reads for analysis. The Tcl scripting language was chosen to support the OpenSees commands, which are used to define the problem geometry, loading, formulation, and solution (Mazzoni et al., 2006). The program can perform analyses for either driven or bored piles, with closed-ended steel or concrete pile material specification for driven piles.

Skin friction resistance at each pile-soil node along the pile-soil profile is automatically generated using the OpenSees *TzSimple1Gen* command (Brandenberg, 2004) and thereby constructs the T-z curve with the TzSimple1 material (Boulanger, 2003b) for use with the zero-length vertical soil spring elements resisting skin friction. The backbone of the nonlinear T-z curve for clay is approximated using Reese and O'Neill's (1987) relation (Fig. 5a), and the backbone of the T-z curve for sand is approximated using Mosher's (1984) relation (Fig. 5b). Similarly, the QzSimple1 (Boulanger, 2003b) command

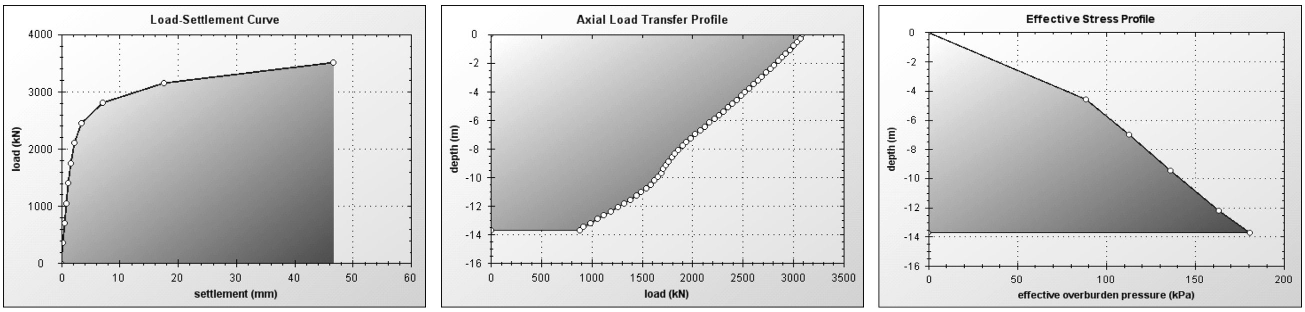



(a) (b)

Fig. 5. Nonlinear T–z curves: (a) T–z curve for clay (Reese and O'Neill, 1987), and (b) T–z curve for sand (Mosher, 1984).


(a) (b)

Fig. 6. Nonlinear Q–z curves: (a) Q–z curve for clay (Reese and O'Neill, 1987), and (b) Q–z curve for sand (Vijayvergiya, 1977)




(a) (b) (c)

Fig. 7. OpenSees ALPile graphical output: (a) load–settlement curve, (b) load–transfer profile, and (c) effective–stress profile

in OpenSees constructs the Q-z curve for any given soil property for use with the zero-length vertical soil spring element resisting end-bearing at the pile tip. The backbone of the nonlinear Q-z curve for clay is approximated using Reese and O'Neill's (1987) relation (Fig. 6a), and the backbone of the Q-z curve for sand is approximated using Vijayvergiya's (1977) relation (Fig. 6b). A more detailed description of the T-z and Q-z formulation implemented in this study can be found in the OpenSees user manual (Mazzoni et al., 2006).

Result data files are then generated after the analysis, in which OpenSees ALPile reads back for output into graphs such as the load-settlement curve (Fig. 7a), load transfer profile (Fig. 7b), and effective stress profile (Fig. 7c). The flowchart of the program algorithm development is summarized in Fig. 8. The ultimate pile/shaft capacity can be evaluated from the load-settlement curve using any recommended criteria from the literature and the codes. The load transfer profile reflects the total capacity of the pile in terms of the

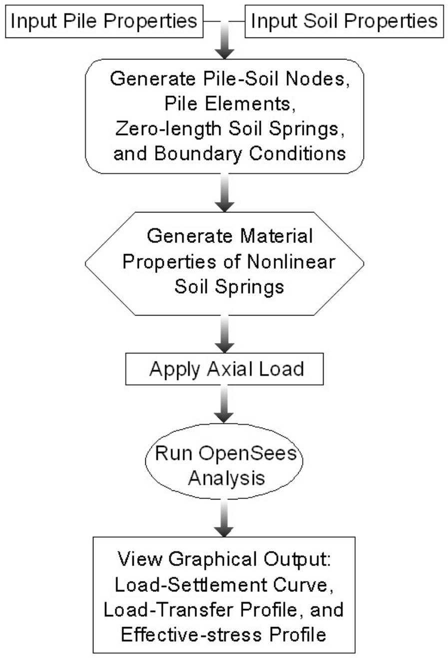



Fig. 8. Program algorithm flowchart for one-dimensional soil-pile analysis

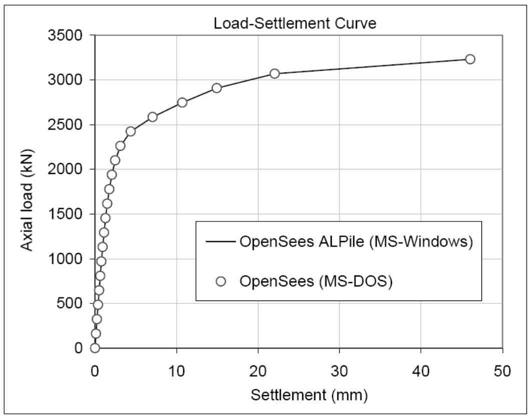



Fig. 9. Comparison of predicted load-settlement curves.

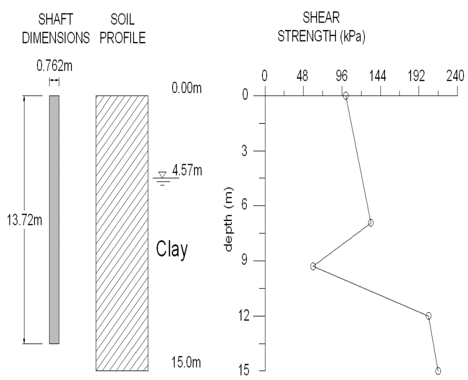
end-bearing and skin friction and their distribution along the soil-pile profile.

## 4. Program Verification and Validation

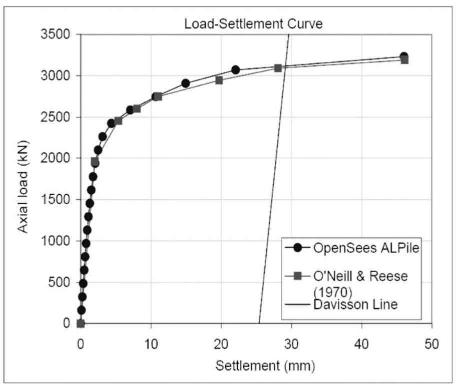
In order to evaluate the accuracy of the axial load capacity and settlement predictions of the program, and to demonstrate its various features, as well as to verify the various formulations implemented in the program code in accordance with the FHWA specifications, various validation analyses were carried out using known soil profiles in clay/sand layers established by several referred authors in the literature who have conducted axial loading tests on single piles and drilled shafts.

For each of the analysis case, the total length of the pile/shaft is divided into 50 segments, at whose ends the T-z springs are attached. The geometrical properties of the pile are entered such as length, diameter, perimeter, cross-sectional area, moment of inertia, and an average elastic modulus property of 25,000 MPa is used in all cases. The depth of the soil profile is entered for each layer along with its properties such as effective unit weights and strength parameters at the top and bottom of the layer. The strength parameter input is defined as the undrained shear strength for clay and angle of internal friction for sand. A comparison of the predicted load-settlement curves for the soil-pile input parameters in Fig. 10a is presented in Fig. 9, which shows equivalent predictions between the DOS program OpenSees and the Windows program OpenSees ALPile and thus validates its performance as a pre/post processor.

The properties of the soil-pile profile shown in Figs. 10a, 11a, 12a, and 13a are entered for each analysis case based




(a)



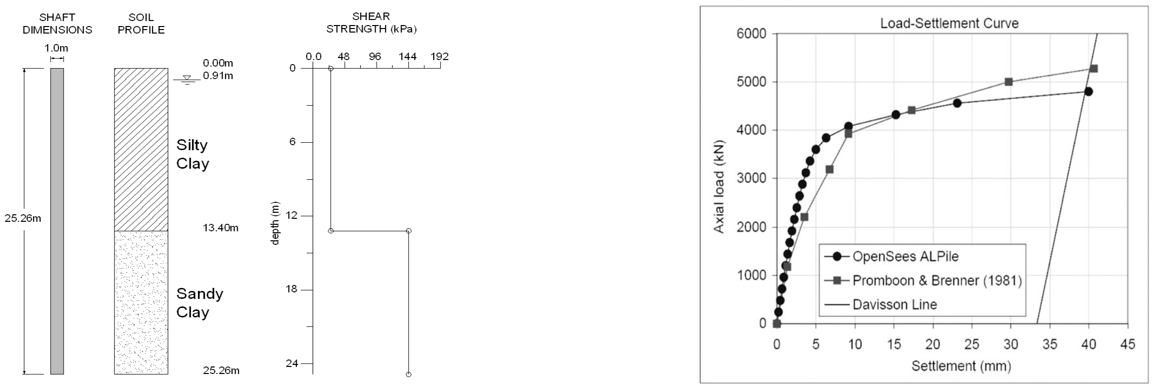

(b)

Fig. 10. 762 mm dia. x 13.72 m bored pile in clay layer: (a) soil-pile profile (O'Neill and Reese, 1970), (b) predicted and measured load-settlement curves.

on data from the respective authors, and the predicted load-settlement curves are compared with the measurements from the results of the axial loading tests. A comparison of the load-settlement curves between the measured capacity and that predicted by the program OpenSees ALPile are shown in Figs. 10b, 11b, 12b, and 13b. Plot of load-settlement, load transfer, and effective stress for the soil-pile profile in Fig. 10a is also shown in Fig. 7.

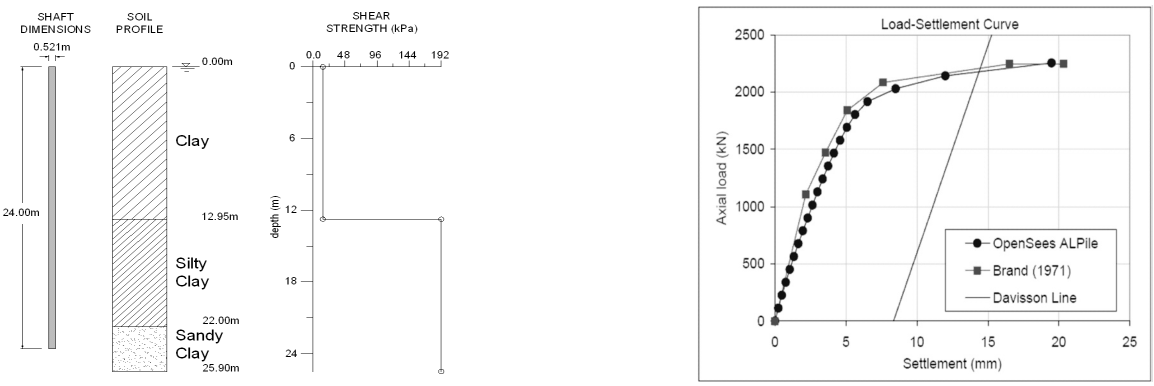
The predicted pile load capacities are evaluated based on comparison with measured data using Davisson's criteria (Davisson, 1976). The Davisson's criteria are one of many methods developed to determine the pile capacity based on static load test results. The steps to obtain the Davisson's capacity are as follows: (1) Plot a line with slope $m$ representing the elastic deformation of the pile, in which $m = AE/L$, $A$ = cross-sectional area of the pile, $E$ = elastic modulus of the pile material, and $L$ = pile length, (2) Draw a line parallel to the elastic deformation line with an intercept $x$, on the settlement (movement) axis as shown in Fig. 14. For shafts with diameter up to 600 mm, Davisson's capacity is defined as the load that causes a shaft top deflection equal to the calculated elastic compression, plus intercept x, equal to 4 mm plus 1/120 of the shaft diameter in millimeters ($x$ = 4 mm + $D$/120). For shafts with diameter larger than 600 mm, FHWA presents a new specification for Davisson's pile capacity as the load that causes a shaft top deflection equal to the calculated elastic compression, plus intercept $x$ equal to 1/30 of the shaft diameter in millimeters ($x = D/30$). The Davisson's capacity (point D on Fig. 14) is defined as the intersection point between the load-settlement curve and the elastic deformation line.

The results have shown that the predicted load-settlement capacity in Fig. 10b is in close agreement with the measurement from axial loading test as indicated by the Davisson line intercept. Results in Fig. 11b shows the predicted pile capacity underestimates the measured capacity by about 9%



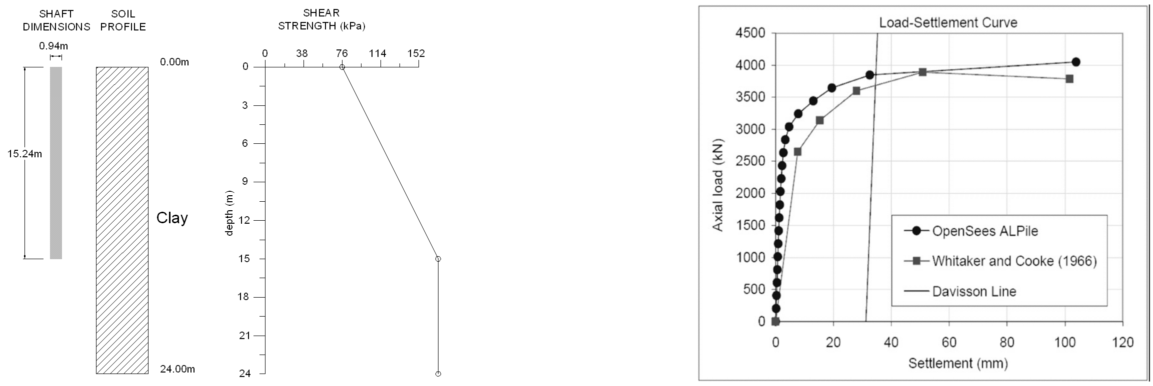

(a) (b)

Fig. 11. 1000 mm dia. x 25.3 m bored pile in silty/sandy clay layers; (a) soil-pile profile (Promboon and Brenner, 1981), (b) predicted and measured load-settlement curves.




(a) (b)

Fig. 12. 521 mm dia. x 24 m bored pile in clay/silt/sandy clay layers; (a) soil-pile profile (Brand, 1971), (b) predicted and measured load-settlement curves.




(a) (b)

Fig. 13. 938 mm dia. x 15.24 m bored pile in clay layer; (a) soil-pile profile (Whitaker and Cooke, 1966), (b) predicted and measured load-settlement curves.

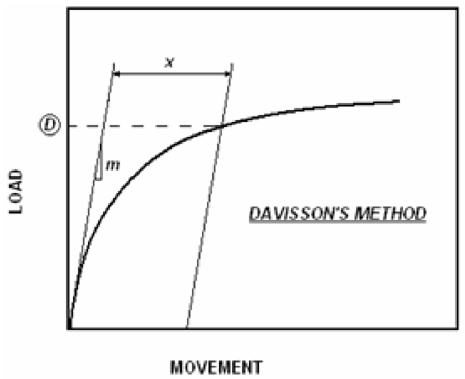



Fig. 14. Construction of Davisson's pile capacity.

and underestimates the settlements within the elastic range. Results in Fig. 12b shows the predicted pile capacity underestimates the measured capacity by about 2% and overestimates the settlements within the elastic range by a few millimeters. In Fig. 13b the predicted pile capacity overestimates the measured capacity by about 3% while underestimates the settlements within the elastic range. The slight variations in the results in some cases could be attributed to the empirical formulations that are implemented in the program based on the established FHWA specifications and guidelines, particularly on the adhesion factors for the computations of soil-pile shear strength and shape of the nonlinear load transfer curves. The method of capacity and settlement prediction of single piles and shafts using nonlinear load transfer curves that is implemented in the program is still shown to have a generally fair correlation with measured data from the references.

## 5. Conclusion

The use of nonlinear load transfer curves to model soil-pile interaction in skin-friction and end-bearing has been shown to capture the nonlinear soil-pile response under settlement due to load. This study has also extended and enhanced the general purpose software MS-DOS program OpenSees into an MS-Windows special purpose computer program that provides an alternative means for evaluation of the static axial load capacity and settlement of single piles and shafts using nonlinear load-transfer curves, with a graphical user interface for a user friendly input and graphical output generation and as well as serving as a preprocessor and postprocessor. The analysis formulations for axial load capacity and settlement predictions have been implemented in accordance with the FHWA specifications for driven piles and drilled shafts. Numerous verification studies have validated the static load capacity and settlement predictions that are in fair agreement with various loading tests found in the literature. With this development, OpenSees can be more accessible both to the research community in the academy and practicing engineers in the industry to aid in the capacity prediction of single piles and shafts.

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