Time-dependent capacity of piles in clayey soils by dynamic methods

De la capacité dépendante du temps des pieux dans des sols d'argile par des méthodes dynamiques

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ABSTRACT: Reliability of dynamic methods for determination of pile capacity is particularly important for piles driven in clayey soils. This paper shows the conditions for proper comparison of static load test and dynamic testing results, analyzes the causes of erroneous prediction of pile capacities computed by wave equation analysis, and demonstrates that application of a variable damping coefficient can improve the reliability of wave equation solutions.

RESUME: La sûreté de méthodes dynamiques pour déterminer la capacité des piles est particulièrement importante pour les piles foncées dans des sols d'argile. Ce papier montre les conditions pour la comparaison convenables de l'épreuve statique de route et des résultats dynamiques d'épreuve, analyse les causes de prédiction erronnée des capacités des piles calculées par l'analyse d'équation d'onde, et démontre que l'application d'un coéfficient d'atténuation variable peut améliorer la sûreté de solutions d'équation d'onde.

1 INTRODUCTION

The capacity of a driven pile changes with time after installation. Soil consolidation and dissipation of excess pore pressure generated during pile driving in the soil-pile interface zone are usually accompanied by an increase in pile capacity. In clayey soils, Seed & Reese (1955) and also Thorburn & Rigden (1980) found an increase in pile capacity (also called setup factor) of up to 6 times over a period of 30 days. In clays, Svinkin et al. (1994) reported the range of setup factors between 4.5 and 11.4 for a period of 22-35 days. Therefore, the assessment of the actual pile capacity after the completion of driving is important for reliable and economic design of pile foundations.

In practice, pile capacity is verified by static and/or dynamic tests. Also, there are predictive numerical computations of the pile capacity such as dynamic formulas and wave equation analysis.

This paper considers some aspects of verification of dynamic testing results and proposes a variable damping coefficient as a way to increase accuracy and reliability of wave equation analysis in predicting pile capacity in clayey soils.

2 ADEQUACY OF STATIC AND DYNAMIC TESTS

It is common in practice to predict the pile capacity by static analysis based on results of in-situ and/or laboratory soil property tests. The static axial load test (SLT) is traditionally used to confirm the computed soil resistance and to determine the service load that can be supported by a pile. The procedure consists of driving the pile to the design depth and applying a series of static loads.

Over the past 30 years, Dr. G.G. Goble and associates pioneered the development of pile capacity calculations from measured force and velocity at the pile head. Dynamic pile testing has become wide spread as a replacement for or supplement to SLT because of its inherent savings in cost and time. Dynamic testing methods are described in Goble et al.(1980), Rausche et al. (1985), Hannigan (1990), Holeyman (1992). These methods allow monitoring pile driving and restrikes, identifying problems during driving, and providing inspection of driving quality for many kinds of piles. To obtain reliable ultimate resistance, it is necessary that the long term pile capacity be fully mobilized. Dynamic testing methods can determine static capacity at the time of testing, at the end of driving or at restrikes. This is a substantial advantage, because dynamic tests can be easily repeated and, consequently, there is an opportunity to obtain pile capacity as a function of time as well as pile embedment.

In spite of a number of problems with implementation of the SLT and interpretation of the ultimate pile capacity, the SLT is considered as the most reliable method to determine pile capacity (Poulos & Davis 1980; Fellenius 1980; Edde & Fellenius 1990).

Because dynamic testing (DT) is often used to replace the SLT, it is important to ascertain the adequacy of both SLT and DT.

Static and dynamic methods to determine the ultimate pile capacity are based on different physical principles, but when both tests are performed on the same pile, they can yield results which together present the pile capacity as a function of time (Svinkin et al. 1994). For different piles driven in clayey soils, time dependent pile capacity can be expressed by relationships such as a linear equation in a logarithmic time scale (Scov & Denver 1988). By way of illustration, the pile capacities from SLT and DT are shown in Figure 1 and Table 1 for a 610 mm square prestressed concrete pile with a 305 mm diameter hollow center. Setup factors were 3.42, 5.73, 6.25 and 6.90 for restrikes 1, 2, 3 and SLT, respectively, Table 1. The depth of pile penetration was 24.4 m, and the soil consisted of about 25.6 m of mainly gray clays followed by a bearing layer of silty sand. The water table was at the ground surface. A Delmag 46-13 hammer was employed for both initial driving and restrikes (RSTR). Driving data are shown in Table 2. In Figure 1, variable t is the time after the end of initial driving (EOID) and for this example t_0=1 is the time elapsed after EOID from which an increase in pile capacity is linear on a logarithmic time scale (t_0=time from EOID to the first restrike in days).

SLT and DT present different ways in determining pile capacity at various times after pile installation, but two principal conditions have to be the same for both kinds of tests. It is absolutely necessary that static and dynamic capacities are being compared only at the same time of testing of both SLT and DT. Moreover, the ultimate pile capacity can be obtained by SLT only if SLT provides the fully mobilized pile capacity similarly to DT.

Table 1. Ultimate Pile Capacity from Static and Dynamic Tests

Test	Time after EOID (days)	Ru (kN)	Ratio R_u/R_{uo}	Setup R_u/R_e
EOID	-	267	-	1
RSTR-1	1	912	1	3.42
RSTR-2	10	1530	1.68	5.73
RSTR-3	18	1672	1.83	6.26
SLT	31	1841	2.02	6.90

R_e is ultimate pile capacity at EOID
R_u and R_{uo} are ultimate pile capacities after EOID at times t and t_o, respectively

The adequacy of SLT and DT have to be confirmed by proper correlation of dynamic methods. It is known that dynamic testing methods yield pile capacity only for the time of testing (Rausche et al. 1985, Likins et al. 1988). Some published data demonstrate comparison of SLT and DT results without taking into account the time between different tests (Rausche et al. 1985, Denver & Skov 1988, Hunt & Baker 1988, Hannigan 1990, Paikowsky & Chernauskas 1992, Lee et al. 1996, Liu et al. 1996). Such a comparison is invalid for piles driven in clayey soils because the results of DT do not correspond to those of SLT i.e. soil consolidation is taken into account for DT and is not for SLT. A statistical approach for comparison of SLT and DT results (Likins et al. 1996, Paikowsky & Chernauskas 1996) is also unacceptable for piles in clayey soils, because this approach demonstrates correlation of setup factors rather than correlation of dynamic methods.

In clayey soils, due to consolidation phenomenon, comparison of SLT and DT can only be made for tests performed immediately one after other. In practice, it is sometimes difficult to make two immediately successive tests, but nonetheless the time difference between both comparable tests should not exceed 1-2 days while soil setup changes only slightly. Such comparison of SLT and DT ought to be made in order to clarify the reliability of pile capacity in clayey soils obtained by dynamic testing.

Table 2. Driving Data

Test	Penetration Resistance (blows/0.3 m)	Rated Energy (kJ)	Rated Transfer Efficiency	Friction (%)
EOID	10	34.13	0.382	79
RSTR-1	21	28.44	0.319	85
RSTR-2	72	23.77	0.266	76
RSTR-3	144	19.77	0.222	75

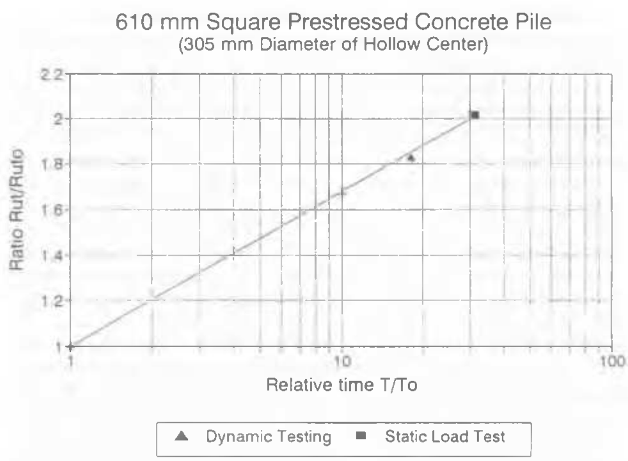

FIG. 1. Pile Capacity-Time Relationship

3 PREDICTION OF PILE CAPACITY

Much effort has been made to devise a correlation between pile capacity and penetration resistance for driven piles. Numerous dynamic formulas have been proposed and wave equation methods have been derived.

The dynamic formulas have been widely used to predict pile capacity, however, it is often observed that the dynamic formulas do not provide very reliable prediction since the input variables such a driving energy and a set per blow are not accurately determined (Chellis R.D. 1961, Poulos & Davis 1980).

The main goal in using the wave equation method is to provide a better prediction of the pile capacity, as a function of pile penetration resistance, than can be obtained from classical dynamic formulas. Today, the most commonly used wave equation programs are based on either WEAP (Goble & Rausche 1976) or TTI (Hirsch et al. 1976).

Application of the wave equation to pile driving analysis is based on Smith's mathematical model of the hammer-pile-soil system (Smith 1960). There is some uncertainty in the wave equation analysis of pile driving because actual efficiency of the entire hammer assembly is unknown (Hannigan et al. 1996). Adjustment of WEAP input with maximum measured values of force, energy and velocity improves WEAP solutions. However, in numerous case histories, computed pile capacity is not equal to the results of static or dynamic tests. It is necessary to make a second adjustment of WEAP input data based on soil parameters (Svinkin 1995) to obtain similar results.

Proper calculation of the dynamic resistance is important for accurate and reliable prediction of static pile capacity. Existing dynamic models of the pile-soil system use a velocity-dependent approach for calculation of the dynamic resistance. This approach requires a damping coefficient for the dynamic resistance during pile driving. There are various linear and nonlinear relationships between damping coefficient and velocity. For a certain pile capacity, the dynamic resistance depends only on pile velocity and the damping coefficient. The pile velocity considered here is the particle velocity at the head of the pile and affects the dynamic shaft and toe resistances.

On the basis of published and measured data, it was concluded (Svinkin 1996b) that peaks of normalized particle velocities along pile shafts are mostly independent of the kind of dynamic testing used and driving conditions with the exception of easy driving. Consequently, measured and computed shaft particle velocities do not reflect soil consolidation as a function of time following pile installation. The pile-soil system changes with time after the completion of driving, but the pile particle velocity stays within a range and is nearly the same for EOID and RSTR. The largest values of particle velocity measured at the pile head and computed along a pile shaft depend mostly on pile parameters and energy transferred to the pile and cannot reflect, by themselves, regain in soil strength and pile-soil adhesion after EOID. However, there are numerous experimental investigations of the Smith soil parameters, damping and quake, for driveability analysis, for example, Litkouhi & Poskitt 1980. Nevertheless, successful in-situ or laboratory measurements of soil parameters does not necessarily guarantee the accurate and reliable prediction of pile capacity. The basic disadvantage of many idealized models is an attempt to select the model parameters in connection with actual soil properties. This can yield acceptable results for some cases, but in general this approach cannot be used to find good correlation between predicted and measured pile capacity after EOID. Neither the pile particle velocity nor a single value of the damping constant can reflect variation of the pile-soil system after EOID.

Though wave equation analysis is an excellent tool for driveability calculations, this method apparently cannot predict reliable pile capacity for various elapsed times after EOID because existing programs, for example, WEAP and TTI do not take into account changes of soil properties after pile installation. The most recent GRLWEAP version of February 1995 uses a setup factor 2.5 for clays and does not require wave equation analysis at restrikes for determining pile capacity. This simple approach is similar to calculation of pile capacity by dynamic formulas and does not demonstrate good GRLWEAP capabilities.

Statistical analysis of a GRLWEAP results (Hannigan et al. 1996) computed for 99 piles driven into various soils has demonstrated that WEAP does not have an advantage in comparison with Gates formula (Poulos & Davis 1980). Mean and coefficient of variation of obtained results are almost the same for both prediction methods.

4 IMPROVEMENT IN WEAP RELIABILITY

Clearly, at each restrike, the pile-soil system has different soil stiffness, damping and mass of soil involved in vibration. For the idealized Smith model, it is desirable to find an appropriate combination of parameter values, mainly paying attention to soil variables, in order to obtain a reliable prediction of pile capacity. Probably, there is no other alternative to enhance prediction accuracy of the dynamic resistance with the particle velocity-dependent approach. The variability of the pile-soil system after the completion of driving can be taken into account by varying the damping coefficient. The damping coefficient should be considered as a function of either time or some other parameter characterizing soil consolidation around the pile. For example, the soil shear modulus or the frequency of the first mode of the pile-soil system could be used (Svinkin 1996a). It is further assumed that the variable damping coefficient is independent of pile velocity.

The dynamic resistance and the damping coefficient as a function of time after pile installation are found on the basis of back-wave equation analysis of the pile-soil system with known pile capacity. Actually, damping and quake determine the soil behavior in the wave equation method, but the damping effect on pile capacity is more important than the quake. A better way to attain the best pile capacity match would be to vary the damping coefficient while keeping the rest of the model parameters constant. Soil damping is the key parameter for adjustment of wave equation solutions with time-dependent soil properties. Adjustment of soil damping is done after adjustment of

Table 3. Wave Equation Analysis. Details of Case Study

Test	Damping Coefficients for Soil Damping Models									
	Standard Smith		Viscous Smith		Case		Coyle-Gibson		Coyle-Gibson/GRL	
	Shaft (s/m)	Toe (s/m)	Shaft (s/m)	Toe (s/m)	Shaft	Toe	Shaft $(s/m)^{0.2}$	Toe $(s/m)^{0.2}$	Shaft $(s/m)^{0.2}$	Toe $(s/m)^{0.2}$
EOID	0.656	-	0.656	-	0.046	-	0.85	-	0.85	-
RSTR-1	1.180	0.492	1.110	0.492	0.285	0.022	0.86	0.19	1.39	0.19
RSTR-2	2.350	0.492	2.030	0.492	0.787	0.063	1.61	0.19	2.32	0.19
RSTR-3	3.920	0.492	3.240	0.492	1.370	0.070	2.23	0.19	3.38	0.19

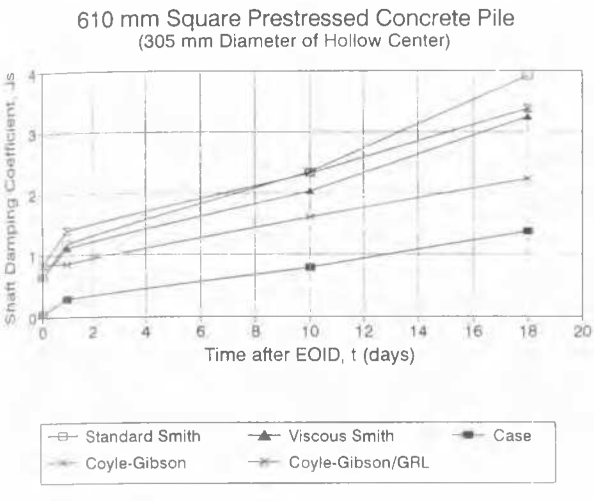

FIG. 2. Shaft Damping as Function of Time

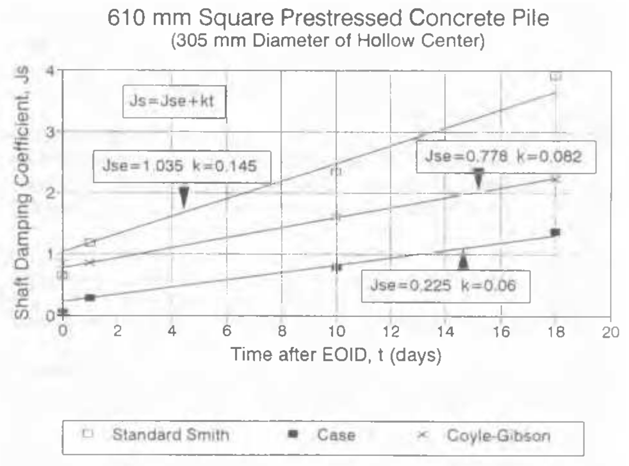

FIG. 3. Shaft Damping-Time Relationship

computed force, energy and velocity based on their measured values. The damping coefficient should be chosen for the predominant resistance, either shaft or toe.

Determination of the dynamic resistance and the variable damping coefficient are demonstrated for the pile described earlier. Five soil damping options available in the GRLWEAP program were investigated: Standard Smith Damping, Viscous Smith Damping, Case Damping, Coyle-Gibson Damping, and Coyle-Gibson/GRL Damping. Analysis was performed in the following manner. Pile capacities and percentage of skin friction were taken from CAPWAP (CAse Pile Wave Analysis Program) analyses of dynamic testing. The tested pile had a predominate shaft resistance at EOID and restrikes. For the damping models considered, the shaft damping coefficient for EOID and the toe damping coefficient for RSTRs were kept constant and their values were chosen in accordance with recommendations contained in GRLWEAP and the literature.

For each dynamic test, WEAP was run repeatedly to match computed and measured values of force, energy and velocity. Then the damping coefficient was adjusted to correlate between pile capacity and blow count per 0.3 m for the best match of WEAP solution and measured pile capacity from dynamic testing with accuracy within 5 %. This procedure was performed for the five damping options mentioned above. Results are shown in Table 3 and in Figure 2. A trend of damping coefficient increase with time after EOID was found for all considered dynamic soil models, and this tendency is independent of the damping resistances. For all considered soil damping laws, the shaft damping coefficient, J_s, as a function of time is well approximated with a linear function starting from a value obtained at RSTR-1 (Figures 2 and 3). Intersections of these lines with the vertical axes provide the values of the initial damping coefficients, J_{se}, at EOID. So,

$$J_s = J_{se} + kt \qquad (1)$$

where t is the time (days) after EOID; factors k and J_{se} are shown for Standard Smith Damping, Case Damping and Coyle-Gibson Damping in Figure 3.

5 CONCLUSIONS

SLT and DT should be regarded as equal partners in determining the pile capacity at various time after pile installation. It is absolutely necessary that the static and dynamic capacities being compared have been determined at the same time. In clayey soils, comparison of static load test and dynamic testing must be made only for tests performed immediately, in short succession.

The reliability of WEAP solutions is low because neither the pile velocity nor the damping constant can reflect variation of the pile-soil system after EOID.

Results show that for reliable WEAP prediction of pile capacity at any time after the end of initial driving, it is necessary to take into account the changes of the pile-soil system occurring with time. Soil damping is the basic parameter for adjustment of WEAP solutions with time-dependent soil properties.

The derived shaft damping coefficients as functions of time can be used as guides for assessment of pile capacity with respect to the time elapsed after the completion of pile driving in clayey soil.

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