Reliability of statnamic load testing of rock socketed end bearing bored piles

Fiabilité d'un essai de charge Statnamic sur un pieu résistant à la pointe foré dans de la roche

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ABSTRACT
The pile load testing methods could be broadly classified into three categories: static, rapid and dynamic depending on the rate of loading. In this paper, the rapid load testing method referred to as the Statnamic test is discussed. The commonly used analysis method of the statnamic testing referred to as the Unloading Point (UP) method is used successfully for the floating piles but validity of some of the assumptions of the unloading point method to end bearing bored piles is questionable. Due to this problem, other analytical methods such as: Modified Unloading Point (MUP) method, Segmental Unloading Point (SUP) method and other signal matching techniques are introduced by some researches. Therefore, the validity of the unloading point method to rock socketed end bearing bored piles in Sri Lanka is investigated in this paper. This investigation is carried out using the commonly used wave number. Furthermore, the wave equation method, commonly used numerical procedure to model dynamic behavior of piles, is used by the author to investigate the validity of the assumptions associated with the unloading point method to rock socketed end bearing bored piles.

RÉSUMÉ
Les essais de charge sur pieu peuvent en général être classifiés en trois catégories principales : statique, rapide et dynamique, en fonction de la vitesse de chargement. Cet article se concentre sur la méthode d'essai de chargement rapide intitulée « Statnamic ». La méthode communément utilisée pour l'analyse des tests Statnamic est intitulée «Unloading point » (UP). Elle est utilisée avec succès pour le cas des pieux flottants mais la pertinence de certaines de ses hypothèses concernant les pieux résistants à la pointe est discutable. Par conséquent, d'autres méthodes d'analyse, telles que la « Modified Unloading Point » méthode (MUP) et la « Segmental Unloading Point » méthode (SUP) ont été utilisées par certaines études. Cet article examine la validité de l'application de la « Unloading Point » méthode aux pieux forés résistants à la pointe au Sri Lanka. Cette étude est réalisée en utilisant le couramment employé nombre d'onde. De plus, la méthode de l'équation d'onde, qui est communément utilisée dans les études numériques de modélisation du comportement dynamique des pieux, est aussi employée pour étudier la validité de la « Unloading Point » méthode pour les pieux forés résistants à la pointe.

Keywords : Statnamic, bored piles, load testing, unloading point method.

1 INTRODUCTION

The Sri Lankan piling industry is at a cross road at this point in time due to the demand for high capacity foundation elements as a result of the recent interest shown by the property developers on high-rise structures. Therefore, economical design, construction and testing of high capacity large diameter bored piles are very important for successful implementation of such projects. Meeting these challenges effectively require re-thinking on the way foundation design, construction and testing done in Sri Lanka. In this endeavour, efficiency, economy and the effectiveness of the present practices should be investigated and appropriate and relevant new methodologies should be introduced.

The aim of this article is to investigate the possibility of using the pile load testing methodology commonly referred to as 'statnamic' test to the rock socketed end bearing bored piles constructed in Sri Lanka. Even though this testing procedure is new to Sri Lanka, most other countries in the world are using this method to load test drill shafts, driven steel and concrete piles. Unlike in traditions static load testing, where pile is loaded slowly under static conditions, in statnamic load testing pile is subjected to a transient impulse loading. Therefore, the data from statnamic load test should be analyzed to obtain the behavior of the pile under static loading conditions. Eventhough there are number of interpretation techniques available, the accuracy of the different methods depends on the duration of the transient impulse loading, pile properties (Middendrop & Daniels 1996). In this paper applicability of the commonly used Unloading Point Method (UPM) to analyze the statnamic load testing results of rock socketed end bearing bored piles in Sri Lanka is investigated.

2 LOAD TESTING OF PILES USING TRANSIENT IMPULSE LOADING

2.1 *Dynamic load testing*

The pile load testing methods could be broadly classified into three categories: static, rapid and dynamic depending on the rate of loading. In the case of static load testing, load is applied on the pile very slowly whereas in the case of dynamic load testing an impact load is applied on the pile. Impact load is applied by dropping a heavy hammer on the pile during dynamic load testing. The impact applied at the top of the pile will generate a stress wave that propagates through the pile at the wave speed (c). Generally, the wave speed through concrete pile rages from 3500 m/sec to 4500 m/sec whereas that for steel pile is about 5000 m/sec. The stress wave, that travels down a pile of length L, takes $2L/c$ time to reach the pile top after reflection at the toe. Therefore, for a 20m long pile the time taken for the reflected wave to reach the pile top is about 4 to 6 milliseconds. Compared to that time duration, the duration of the impact is very small in the order of 2 to 3 msec. As the pile top is unloaded before the reflected wave reaches the pile top, wave propagation through the pile is the mode of stress transfer.

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2.2 *Rapid load testing*

The statnamic test procedure,, developed by Bermindhammer equipment in 1988, applies a rapid load on the pile due to burning of solid fuel within a pressure chamber, which is directly in contact with the top of the pile as shown in Figure 1. Due to the high pressure generated by the combustion of the solid fuel, upward thrust is applied on set of reaction weights and equal and opposite force will be applied on the pile. The sudden force that is applied on the set of reaction weights sets it off in motion vertically upwards with a vertical acceleration of *a*. If the mass of the reaction weights is equal to *M*, the force, due to combustion F_{Stanam}, required to generate a vertical acceleration of *a* is *Ma*. If the acceleration of the reaction weights is 20g, F_{Stanam}, is twenty times the reaction weight and hence, the applied load on the pile is twenty times the reaction weights. As a result, the reaction load required is 5% of the reaction load required for static load testing. However, if the reaction weights are loosely placed, falling the mass on to the pile after the flight may damage the pile. To prevent this different catching mechanisms are in use.

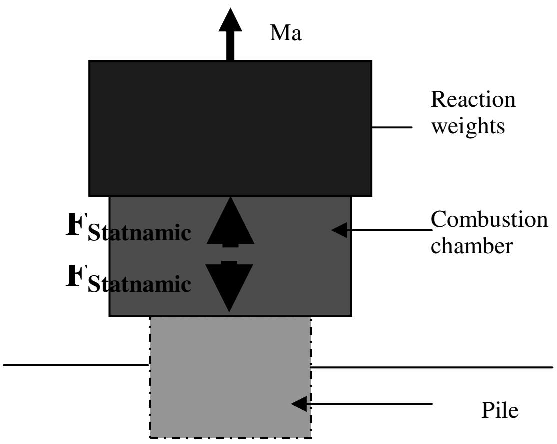

Figure 1 - Schematic diagram of the Statnamic load set up

The duration of the load application is 10 to 100 times that of a hammer blow and the pile acceleration is 100 to 1000 times less than that due to a dynamic load (Research committee on rapid pile load test methods - Japanese Geotechnical Society, 1998). Moreover, the load duration is more than the wave reflection time and, as a result, the pile is loaded, even when the reflected wave reaches the pile top. Therefore, the entire pile is stressed during loading and the wave propagation through the pile is not predominant. This type of loading can be considered as rapid push on the pile top rather than a dynamic impact load. During the test, load applied on the pile is measured using a load cell and the displacement of the pile is measured using a laser beam. The variation of the applied load on the pile with time due to the combustion of the fuel in the chamber of the statnamic device depends on many factors. Among the important factors are the shape and dimensions of the vent, pressure chamber volume, volume and the type of the fuel, mass and the geometry of the reaction mass, and properties of the soil and the pile.

3 ANALYSIS OF STATNAMIC LOAD TEST DATA

Due to the statnamic force acting on the pile, the pile obtains a certain acceleration and velocity. Compared with the acceleration and velocity of a similar pile subjected to high strain dynamic load testing using PDA, the acceleration of the pile is relatively small at about 1 to 2 g's. However, the resistance acting on the pile contains certain amount of viscous resistance, which should be removed from the statnamic force to obtain the static response. Analytical methods available to interpret statnamic load test results may be categorized into following groups:

i. Intuitive interpretation methods;
ii. Analysis using concentrated mass models;
iii. Signal matching using numerical simulation methods;
   a. Analysis using one dimensional stress wave propagation theories; and
   b. Finite element methods.

The most widely used method to estimate the static response of a pile from statnamic test is the concentrated mass model, commonly referred to as the Unloading Point (UP) method (Middendrop 1992).

3.1 *Unloading Point (UP) method*

In the UP method, pile-soil system is modeled using a simple single degree of freedom system. The mass of the pile is lumped and is assumed to be resting on a nonlinear spring and a dashpot (Mullins et al. 1992). The nonlinear spring represents the elastic response of the pile and that of the surrounding soil while the linear dashpot represents the dynamic (or viscous) resistance of the surrounding soil. Two main assumptions were used in the UP method of analyzing statnamic load test results:

i. The pile plunges due to application of the statnamic force and the resistance during plunging is constant; and
ii. The damping constant is constant during the entire test.

The equation of motion of the mass *m* can be represented by the following mathematical equation:

$$F = ma + Cv + kx \quad (1)$$

Where
F - Statnamic force
a - Acceleration of the pile
v - Velocity of the mass *m* and
k - Displacement of the mass *m*

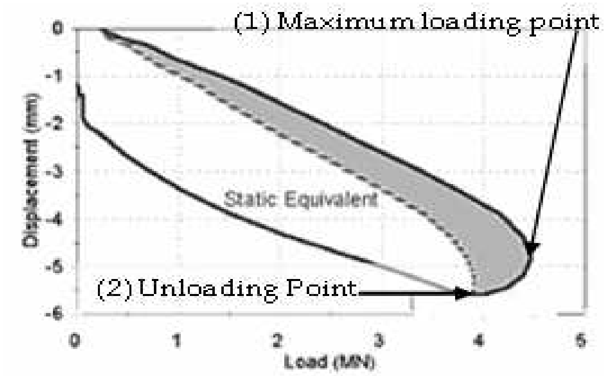

Figure 2 - Static equivalent load – settlement curve from stanamic test results

The measured force on the pile head with time during a statnamic load is shown in Figure 2. As the pile velocity is zero at the unloading point, the force measured during statnamic test is equal to the static force. It is assumed that the pile is in motion from the maximum loading point up to the unloading point with the static force (spring force) obtained at the unloading point. Therefore, an equivalent damping factor is calculated for that region using Equation (1), as the velocity of the pile is known from the test. Estimated damping factor is multiplied by the velocity of the pile to obtain the damping force during the statnamic loading. The damping force, thus estimated, is subtracted from the force measured during statnamic load testing to obtain the static load applied on the pile, as shown in Figure 2, and hence, static load \settlement response of the pile.

The validity of the unloading point method was expressed by (Middendrop & Daniels 1996) through a parameter called wave number (N_w), which is defined as the ratio of the wave length (D) and the length of the foundation (L). The wave length (D) is obtained by multiplying the wave speed (c) by the duration of the statnamic loading. (Middendrop & Daniels 1996) showed that if the wave number is more than 12, the unloading point method can be used to accurately predict the static behavior. Using a one dimensional wave propagation model, Nishimura et al. (1998) suggested that the boundary between dynamic and statnamic load test lie around the wave number (N_w) 10.

3.2 *Validity of UP method for bored piles in Sri Lanka*

Data from dynamic load testing of piles using Pile Driving Analyzer (PDA), in which impact load is applied onto the pile using a heavy hammer, was collected to obtain the wave speed through bored and cast in-situ concrete piles in Sri Lanka. Assuming conservative duration (resulting low wave number) of the load during satanamic load testing as 80 msecs, wave numbers (N_w) for the 103 piles were estimated. Figure 3 shows the variation of the wave number N_w with the corresponding pile lengths.

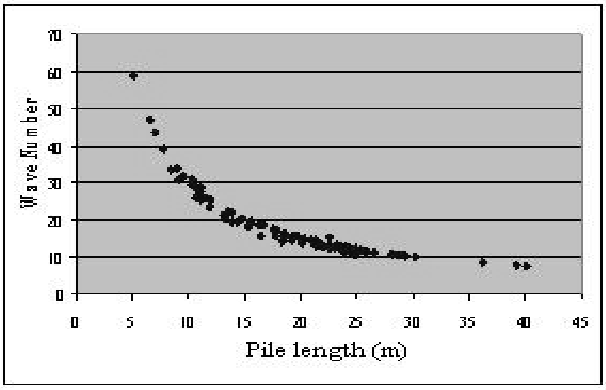

Figure 3 - Wave Number vs. pile length obtained from PDA testing of bored piles

It is clear from Figure 3 that except for 4 piles longer than about 30m, the wave number is greater than 12 for all the other piles considered. Therefore, according to the criterion proposed by (Middendrop & Daniels 1996), UP method could be used to analyze the statnamic load test results of the most of the rock socketed end bearing bored piles constructed in Sri Lanka, as most of the piles are shorter than 30m. If the wave number is less than about 12, likelihood of developing stress wave within the pile is minimal as the loading duration is significantly longer than the time taken for the reflected waves to reach the pile top. However, still if the pile is socketed into the bedrock, there can be a considerable difference between the displacement of the pile top and the pile toe, violating the rigid body motion assumed in the UP method. Therefore, the applicability of the statnamic test to bored piles constructed in Sri Lanka should be closely investigated.

On the other hand, plunging type failure assumed from the maximum loading point upto the unloading point may also be looked into. To investigate the amount of displacement bored piles in Sri Lanka undergo due to dynamic impacts, the author collected data related to high strain dynamic testing of rock socketed bored piles in Sri Lanka. In these dynamic testing using Pile Driving Analyzer (PDA), a heavy hammer is dropped onto the pile to mobilize the skin friction and end bearing of the pile at least upto the test load (normally, 1.5 x working load).

During the PDA tests, the permanent settlement of the pile is measured independently and thus the measured set of the pile due to the impact loading during the PDA testing is available. Figure 4 shows the measured set of the piles and the length of the piles which are subjected to high strain dynamic testing using PDA.

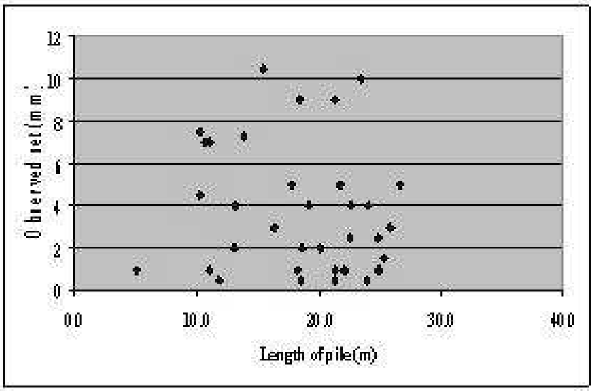

Figure 4 - measured set during PDA testing of piles vs. pile length

Out of the 36 rock socketed bored piles considered in the analysis, only about 8 piles have undergone a set larger than 5mm. Therefore, it is clear that the piles are not subjected to plunging failure, when they are sockected into strong bedrock commonly found in Sri Lanka. As such the assumption of the plunging type failure, if they are subjected to statnamic load testing upto about 1.5 x working load is very low.

4 INVESTIGATION OF THE VALIDITY OF THE RIGID BODY MOTION DURING STATNAMIC LOAD TESTING

If the pile moves as a rigid body the relative displacement between the pile top and the toe should be a small percentage of the total displacement of the pile top. To investigate the displacement of the pile top and the toe, wave equation model proposed by Smith (1960) is used. A computer program was developed to implement the Smith model (Smith 1960) and a triangular stress pulse, with a duration of 80 msec, similar to the one applied on the pile head during statnamic test was applied to the top most element. It should be noted here that the effects of the interaction between the pile movement and the statnamic loading device in the loading pulse was neglected. Dynamic soil parameters for typical subsurface conditions along the pile shaft, obtained from the results of dynamic load test results (Thilakasiri et al. 2006), were used in the modeling process. A 800 mm diameter piles of length 10, 20 and 30m length were considered in the modeling. The variation of the displacement of the pile top and the toe with time for different pile length are shown in Figure 5.

Similarly, the stiffness of the pile toe was doubled the reference stiffness for a 30m long pile and the variation of the pile top and toe displacements are shown in Figure 6. The relative displacement between the pile top and the toe closer to the maximum displacement is very important as the plunging failure is assumed to take place during that time. Table 1 shows the pile top displacement at the unloading point and the corresponding pile toe displacement. It is amply clear that the when the pile length is increased, the, the relative displacement increases and similarly if the stiffness of the pile toe material is increased, the relative displacement increases. For example for a 30m long pile with doubled the reference toe stiffness the displacement of the pile top at the unloading point is 244% of the corresponding toe displacement. In such situation, the rigid body motion assumed in the UP method, eventhough the wave

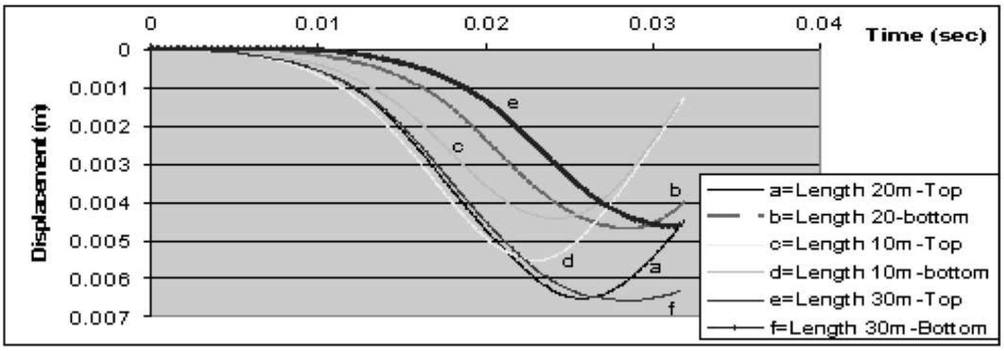

Figure 5 - Estimated pile top and bottom displacement with time.

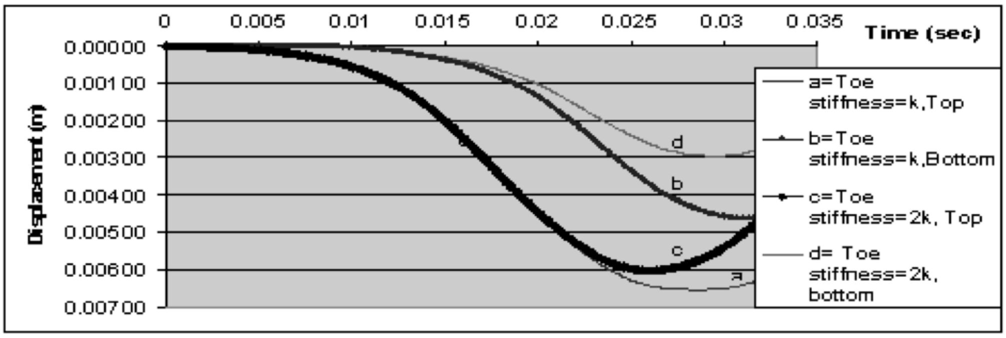

Figure 6 - Estimated pile top and bottom displacement for a 30m long pile with doubled toe stiffness.

number is more than about 12 is not valid. However, if the pile is relatively short, the rigid body assumption is fairly accurate. On the other hand, if a long pile is resting on a harder rock formation, the rigid body assumption may not be accurate. In such situations other refined concentrated mass models such as Modified Unloading Point (MUP) method (Justason 1997), Segmental Unloading Point (SUP) method (Mullins et al. 2001) or other signal matching techniques may be used to analyze the statnamic test data.

Table 1 – Maximum displacement of the pile top and the corresponding displacement of the pile toe.

Pile length (m)	Toe stiffness	Maximum pile top displacement[a] (mm)	Corresponding toe displacement[b] (mm)	% of (a/b)
10	k	5.6	4.4	127
20	k	6.4	4.4	145
30	k	6.6	4.3	153
30	2k	6.1	2.5	244

5 CONCLUSION

The applicability of the commonly used Unloading Point (UP) method to analyze the statnamic load test data of the rock socketed end bearing bored piles is investigated. The main assumptions involved in the UP method are: (i) The pile should undergo plunging type rigid body motion during the application of the statnamic force and; (ii) The stress wave propagation through the pile should be minimal. It was revealed that if the length of the pile is less than about 30m, the stress wave propagation through the piles is not that critical. Further, the assumption of the rigid body movement of the pile was investigated using the Smith wave equation method of analysis. The analysis revealed that the top and toe displacement of the pile increase when the length of the pile and the stiffness of the end bearing material is increased. In such situations, the use of the UP method can give rise to significant errors and other more detailed data analysis methods should be carried out.

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