IMPROVED METHODS FOR RAPID LOAD TESTS OF DEEP FOUNDATIONS

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ABSTRACT

Rapid Load Tests have been promoted as an alternative for Static Pile Load Tests since the late 1980s. Rapid Load Tests create a relatively long duration force pulse in comparison with Dynamic Load Tests. However, a reliable prediction of pile static capacity with this test based on the so-called Unloading Point Method (UPM) has been subject to debate. Estimates of static capacity by UPM have overestimated static load test results when the applied force pulse produced too little axial movement. To resolve these issues, a drop mass Rapid Load Test called the Hybridnamic Test (HT) was developed with a ram mass up to 700 kN to reliably estimate the pile static ultimate bearing capacity up to a 35 MN. This paper discusses using a multi-cycle Hybridnamic Test in soil of mostly sand. A new interpretation method called Fully Mobilized UPM, with a required minimum net penetration per test cycle, was applied to this case study and comparison of estimated soil resistance was made between conventional UPM and Fully Mobilized UPM, and with signal matching of the dynamic force pulse data using CAPWAP. Finally a practical method to prepare a Static Load-Displacement Curve based on multi-cycle HT results is proposed.

INTRODUCTION

Rapid Load Tests (RLT) have been promoted as an alternative for Static Pile Load Tests since the late 1980s. Compared with Dynamic Load Tests, Rapid Load Tests create a relatively long duration force pulse by either a combustion process (i.e.

Statnamic Test, Bermingham & Janes, 1989) or an impact of a cushioned drop mass (i.e. Pseudo Static Test. Schellingerhout & Revoort, 1996). In 2002, "Method for Rapid Load Test of Single Piles," standardized by the Japanese Geotechnical Society, adopts the Unloading Point Method (UPM), which regards the test pile as a lump mass with a spring and a dashpot as shown in Figure 1. The force at the point when displacement is maximum (e.g. velocity is zero) is chosen to eliminate dynamic damping effects so the force at that time is then the ultimate static resistance. The UPM underestimates the static capacity compared to static load test results when the force pulse test has too little energy. On the other hand, estimates of static capacity usually significantly overestimate static load test results when the force pulse test has produced too little permanent axial movement, particularly in cohesive soil conditions due to the rate effect. Reliable prediction of static capacity with this test may be questionable because of the reasons below:

1. The UPM model lacks a slider element and therefore it is unable to separate the static resistance effect from the dynamic resistances, particularly in clay.
2. Longer piles cannot be considered a single lump mass for a short force pulse.
3. If end bearing is not fully mobilized, it is impossible to predict ultimate capacity.

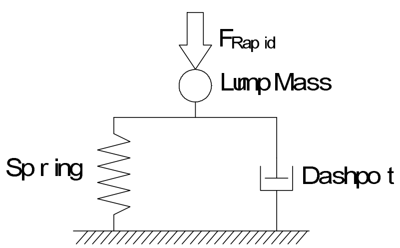

FIG.1. Model for UPM

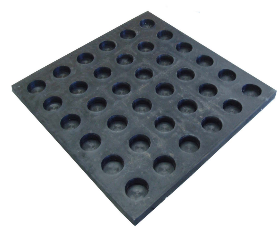

FIG. 2. Single Hybridnamic cushion sheet

In addition, nonlinear soil properties increase the difficulty in estimating the ultimate soil resistance. Generally soil resistance assessable by UPM in one testing cycle is closely associated with the maximum applied force and energy transferred to the test pile during the force pulse and resulting net permanent movement. Therefore, a multi-cycle testing method may be necessary to assess ultimate soil resistance.

To resolve the above issues, a variation of the drop mass Rapid Load Test called the Hybridnamic Test (HT), developed in 2005, is equipped with a modular ram of up to 700 kN and a hybrid cushion with low resilience. HT is able to transfer sufficient energy to the test pile to totally activate and to estimate reliably the pile static ultimate bearing capacity up to 35 MN. The cushion block is assembled by stacking in parallel and/or in series single cushion sheets (primarily shaped rubber), as shown in Figure 2. The practical maximum force pulse duration is about 0.2 second.

A case study presents a multi-cycle Hybridnamic Test in soil consisting primarily of sand, with some thin layers of silt and stiff clay. A new interpretation method called Fully Mobilized UPM, in which a minimum net penetration per test cycle is required, was applied to this case study to estimate the ultimate soil resistance. Estimated soil resistances from conventional UPM and Fully Mobilized UPM were compared with results of a static load test. Comparison is also made with signal matching of the dynamic force pulse data using the CAPWAP® software program.

CASE STUDY OF HYBRIDNAMIC TEST

In this case study, the testing frame and equipment shown in Figure 3 was used. This equipment consists of a ram with a mass of 70 kN, a stacked cushion with spring constant of 74.0 MN/m and with dimension of 0.72 x 0.72 x 0.15 m, and a 6.5 m high frame, which allows for a 2.0 m ram drop. Thus, this equipment can apply a force pulse with duration greater than 31.0 ms. This duration represents the time required for a stress-wave to travel more than six times upward and downward along the pile, exceeding the Japanese standard requirement (five round trip passages) for RLT.

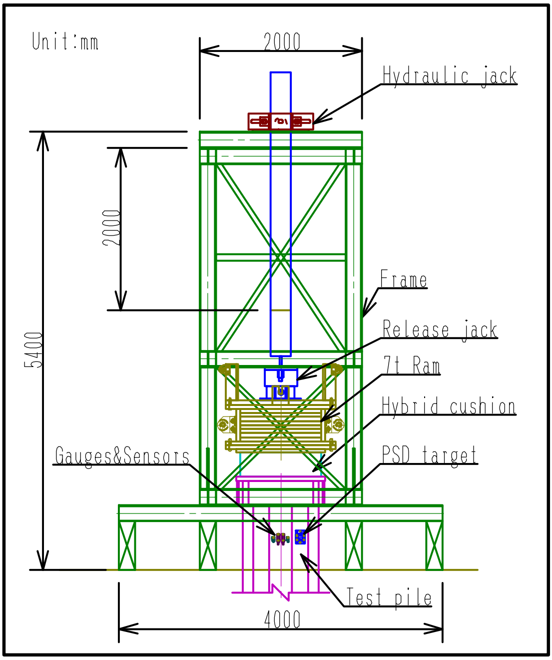

FIG. 3. Test frame and equipment (70 kN ram).

The test pile was a Type-10H steel sheet pile. This pile type has dimensions of 900 x 230 mm, a thickness of 9.2 to 10.8 mm, a perimeter of 2.3 m, pile length of 12.5 m, and has a cross-sectional area of 110 cm^2. The test pile was installed using a vibratory hammer.

Soils consist of a 2.9 m thick sand layer (N=10), followed by 2.7 m of silt (N=0), then 5.0 m coarse to gravelly sand N = 10 to 20), followed by a 1.2 m thick layer of stiff, gravelly clay, then dense fine sand beyond (N = 50+). Pile tip is located almost at the bottom of the stiff, gravelly clay layer with N value greater than 50.

Testing Procedures

A Static Load Test (SLT) conducted one month after installation, shown in Figure 4, indicates a yield point at 1.65 MN and ultimate load of 1.8 MN with a permanent pile top displacement of 99.3 mm. The summary of test results is shown in Table-1.

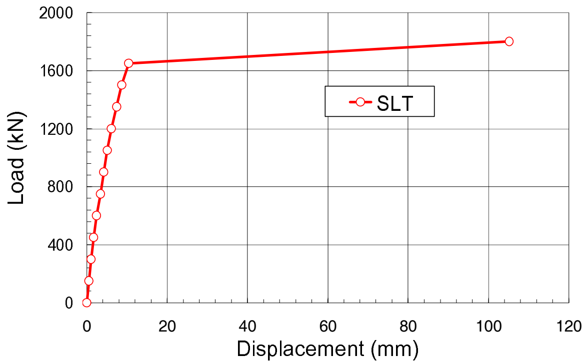

FIG. 4. Static load-displacement curve.

Table 1. Summary of Static Load Test Results

Yield Resistance			Ultimate Resistance		Pile-Soil Stiffness	
Load (kN)	Top Disp. (mm)	Tip Disp. (mm)	Load (kN)	Top Disp. (mm)	Tip Disp. (mm)	Ko (kN/mm)
1,650	11.7	4.8	1,800	106.5	99.3	140

Table 2. Summary of Hybridnamic Test

Drop Height	Pile Top Displacement (Total)	(Permanent)	Soil Resistance (Pile Top)
(m)	(mm)	(mm)	(kN)
0.20	4.8	1.0	1,064
0.60	10.4	2.0	1,994
1.00	15.7	4.0	2,578
1.50 (1)	25.8	16.0	1,762
1.50 (2)	28.6	19.0	1,821
1.50 (3)	29.4	19.0	1,927

The Hybridnamic Test was conducted 8 weeks after the Static Load Test. The ram was dropped from heights of 0.2 m, 0.6 m, and 1.0 m, and then was dropped three times from a height of 1.5 m. Measuring sensors consisted of two strain gages, two accelerometers, one optical displacement measuring device and one permanent displacement checking device. HT results are shown in Table 2.

The measured forces (F; also called the soil resistance Rsoil) and displacement (Δ), obtained from HT and SLT and shown in Figure 5, are normalized by the static ultimate soil resistance (Ru=1800 kN) and pile dimension (900 mm). Figure 5 reveals the following:

1. The curves of the 0.2m drop, 0.6m drop, and 1.0m drop are significantly different in general shape from the curves of the 1.5m drops.
2. When the applied force is less than the ultimate static resistance, the net permanent displacement will be near zero and the UPM underpredicts the ultimate capacity.
3. The soil resistance of the 0.2m drop has greatly underestimated the static soil resistance as compared with the SLT.
4. The soil resistances of the 0.6m drop and the 1.0m drop have overestimated the static soil resistance as compared with the SLT. The result from the 1.0 m drop (e.g. significant overprediction by factor of 1.43) is not necessarily the maximum that would be predicted from UPM if a slightly different drop height were selected.
5. The overprediction possibility can be even larger when the soil is cohesive.
6. The soil resistance of the 1.5m drops are close to the SLT static soil resistance.
7. The normalized maximum and net residual displacements for 1.5m drops of about 3% and 2% respectively are suggested minimum requirements for improved UPM

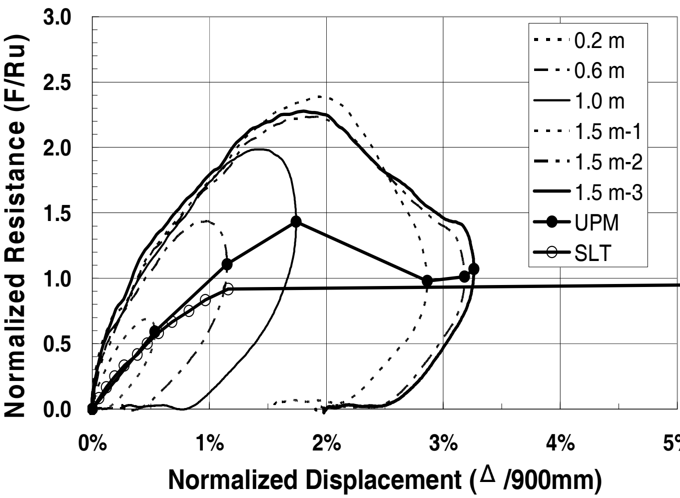

FIG. 5. Rsoil-displacement curve

INTERPRETATIONS

Because the static soil resistance obtained from drop heights under 1.5m (with low net permanent displacement) cannot be accurately extracted from the total response which includes dynamic damping effects, another evaluation method is required. The reason why the soil resistance values from the 1.5 m drop heights are close to that of SLT can be simply explained by the added slider element model shown in Figure 6, compared to the model shown in Figure 1. The Figure 6 model, named "Fully

Mobilized UPM," allows the lump mass to penetrate the bearing stratum and then retain significant permanent displacement. Subjected to significant permanent displacement and full soil resistance mobilization, the dynamic effect can be evaluated and the ultimate static resistance assessed more precisely. From Table 2, the net permanent displacement difference between the drop heights less than 1.5 m and that of 1.5 m is significant. The improved prediction reliability accompanying significant net permanent displacement is obvious from Figure 5.

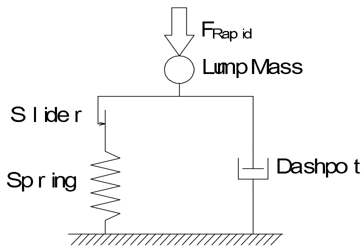

FIG. 6. Fully mobilized UPM model

To separate the dynamic component from the static component, signal-matching analysis of the measured data from various drop heights was also investigated by using CAPWAP (Rausche, 1972). Since full mobilization for a dynamic test requires only 2 mm net permanent set, data from even the 0.60 m drop should be useful. The load – displacement curves obtained from CAPWAP of the 0.60, 1.00 and 1.50 m drops are shown in Figure 7, with an average estimated capacity of 2150 kN. This result is 18 percent larger than the Full Mobilization UPM result. The CAPWAP solutions for low net permanent displacements avoid the large overpredictions of UPM (e.g. for the 1.0 m drop) and are therefore preferred when net displacements do not achieve "full mobilization" during a RLT. Since RLTs often have relatively low net penetration, signal matching may be useful.

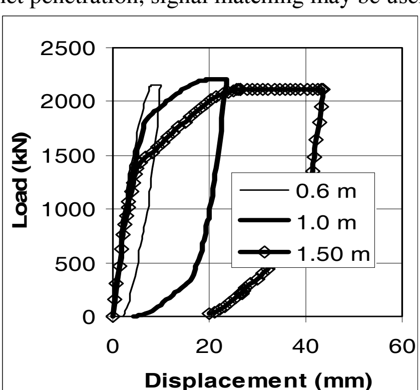

FIG. 7. CAPWAP Load–displacement curves

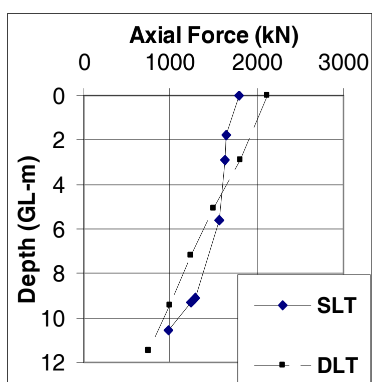

FIG. 8. Axial force distributions

The axial force distribution along the pile obtained from both SLT and signal matching for a 1.5m drop are shown in Figure 8. The two distributions are reasonably similar. Differences are attributed to the relatively long “rise time” in the HT force and velocity data that makes more exact distributions more difficult to obtain.

Preparation of Static Load-Displacement Relationship

A practical method to prepare a curve for static load-displacement from an HT test series is proposed in this study. The detailed procedures are described below:

1. Plot soil resistance versus the maximum displacement obtained from the first low height drop where supposedly the soil resistance remains in elastic domain.
2. Plot soil resistance at the Fully Mobilized UPM versus the displacement of D/10.
3. Complete the curve based on Weibull’s Formula (NIST 2006).

The static load-displacement curve prepared using the above proposed method for this case history (Figure 9) matches well that obtained from the SLT.

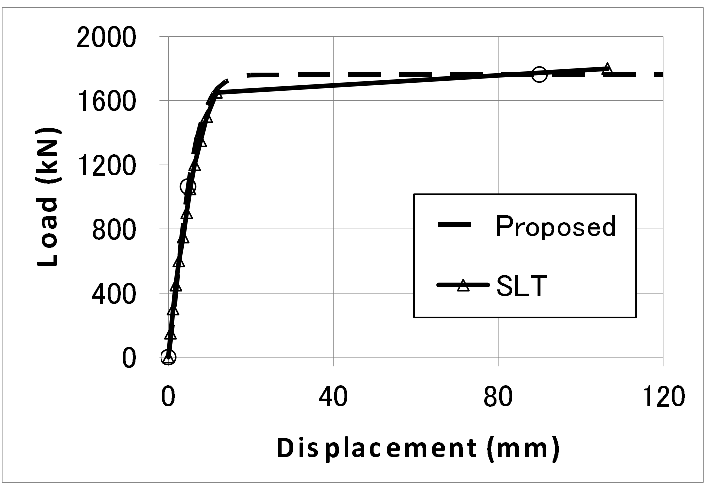

FIG. 9. Static load-displacement curve prepared based on proposed method.

CONCLUSIONS

An improved method for rapid load testing, called the “Hybridnamic Test” was introduced. A new interpretation method called Fully Mobilized UPM was applied to this multi-cycle Hybridnamic Test case study to estimate the ultimate soil resistance. The soil resistance from the Fully Mobilized UPM, requiring sufficiently large net permanent displacement, was compared to a conventional UPM. Comparison was also made with signal matching of the dynamic force pulse data using CAPWAP. Finally a practical method to prepare a static load-displacement curve based on multi-cycle HT results was proposed. Through these studies, the following conclusions were reached:

1. Conventional UPM underestimates the ultimate static resistance from insufficient energy and applied maximum force less than the capacity (e.g. 0.2 m drop).
2. For applied force greater than the ultimate soil resistance, but with low net permanent displacement, the conventional UPM may greatly overestimate the ultimate static soil resistance due to rate effects, even in non-cohesive soils. At low net permanent displacement, even larger overpredictions are likely in cohesive soils.
3. Subjected to sufficient permanent displacement, the total soil resistance can be fully mobilized, and the ultimate static soil resistance can be assessed more accurately. This case history advocates a net permanent displacement of at least three percent of the pile diameter as the suggested minimum limit.
4. When the net permanent displacement is less than three percent of the pile diameter when Full Mobilization UPM does not apply, the most accurate method to determine ultimate soil resistance is to analyze the Rapid Load Test data (for the drop weight method of application) with signal matching such as CAPWAP.
5. The static load-displacement curve prepared based on the proposed method matches well that obtained from the Static Load Test.
6. Base on the authors' experience, it is recommended that the number of loading cycles should not exceed three cycles while the soil resistance remains in the elastic domain, and should not exceed two cycles after the soil resistance is fully mobilized and is in the plastic domain. The optimum number of loading cycles is suggested as three to five.

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