Journal of Civil Engineering
The Institution of Engineers, Bangladesh
Vol. CE 29, No. 1, 2001

DYNAMIC PILE TESTING AND ITS CORRELATION WITH STATIC LOAD TEST

M. Kamal Uddin[1] and Krai Tungsanga[2]

ABSTRACT: Dynamic pile load test involving stress wave measurements has recently been evolved as an advanced method of pile testing where measurements at pile top under a dynamic and impacting mass are used to evaluate bearing capacity of pile foundation. The method has become popular and a routine pile testing device in many countries around the world as it is quick and incurs relatively low cost. The conventional method of static load test is expensive, time consuming and in some cases physically impossible to perform. Due to many limitations, usually only few piles are tested by static load test method on big projects and none in smaller projects. This paper is an outcome of a research project wherein attention is focused to find a correlation of static load test and dynamic load test. The research was carried out on a large project, Don Muang Tollway Project, Bangkok. The paper focuses five case histories where both static and dynamic load tests were performed on the same pile. Soil set-up characteristics at the referenced projects were investigated and compared. Appraisal of dynamic load test were done by comparing dynamic and static load tests. Correlation was made by evaluating the field performance. The results can be used as a basis for construction and design criteria of pile foundation.

KEYWORDS: Dynamic load test, stress wave measurement, static load test, wave transmission speed, CAPWAP, damping factor, Case Method, PDA.

INTRODUCTION

Static load test is a classical pile testing device which is carried out by applying loads of known magnitude to the pile top and then measuring the pile movement. Various analytical procedures are in force for analysis of pile load bearing capacity. The capacity of the pile-soil system may be evaluated by static analysis taking into account of the soil strength parameters derived from both *in-situ* and laboratory tests. Generally, the static bearing capacity of a pile is limited either by structural strength of the pile shaft or the capacity of supporting soils.

---

[1] Institute of Appropriate Technology, Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh.

[2] PDIC Ltd., Bangkok, Thailand.

Structural capacity of pile is limited by allowable stresses of pile which are based on material properties and specification requirements. However, static analyses are considered preliminary and must be supported by additional field tests in most cases. Dynamic pile testing is a state-of-the-art of determination of bearing capacity of pile where dynamic measurements of pile force and motion are recorded during impact of a falling ram which is generally used to evaluate axial static bearing capacity of pile. Continuous development of analytical procedure and measuring device has improved the economy and reliability of the method.

The research was carried out with Don Duang Tollway Project, Bangkok, where stress wave data were utilized to determine bearing capacity of piles. Don Duang Tollway Project is a large project which is along Viphavadi-Rangsit Highway. The project comprises of a 6-lane elevated expressway having a total length of 15km. The foundation to support the superstructure consists of driven piles ranging in size from 600 to 800 mm in diameter. Since conventional static load test is costly and very time-consuming, it was considered that condition of static load tests might cause significant delay of the project. Moreover static load test would occupy large space at the median of Viphavadi-Rangsit Highway which was very narrow as allotted by the Department of Highway, Thailand. Due to these constraints and in order to meet the tight construction schedule and to observe pile & hammer performance, the expensive static load test was supplemented by a more economical and expeditious dynamic load test. The prime objective of the research study was to investigate and find out a correlation between the classical testing method of static load test and more advanced method of dynamic pile testing. This paper presents five case histories (five piles) where both static and dynamic tests were performed on the same pile. It describes the dynamic pile testing and analytical method and discusses the use and merits of both static and dynamic tests.

CLASSICAL METHOD OF PILE TESTING: STATIC LOAD TESTS

In general, testing of pile means application of a static load on the top of a pile and then measuring the resulting movement of pile top (usually test procedure is adopted conforming to ASTM 1143). The failure load is the ultimate load which causes excessive pile movement. In literature, failure load is explained and interpreted in a number of ways (Fellenius, 1980). For a high capacity pile, often a proof test to a certain load level is conducted which is time consuming, too expensive and in some cases it becomes impossible to perform practically. Due to these constraints and difficulties, usually only a few piles are tested in large projects and perhaps none in smaller projects. Normally, in smaller projects, time consuming and expensive load test program is avoided. In many cases, information obtained from only one static load test is used to judge the rest of the piles in a foundation. Many factors such as subsurface variability, use of different types of equipment and construction techniques, variation of workmanship, etc., affect bearing capacity of pile. Thus structural integrity and strength of individual pile can vary widely. So risk exists when such approach of adopting basis of design from very narrow testing is used. Even under very well controlled conditions, the evaluation of piles for ultimate capacity based on static tests can easily contain errors of 10 to 20% with respect to real value (Fellenius, 1980). Static tests can even be totally misleading in some cases (Edde and Fellenius, 1990). Nevertheless, static load testing is still considered to be the best and only means for providing a frame of reference of static bearing capacity of pile. In the case studies, static tests results are discussed. In the analysis, as a failure criterion, the method of Division was chosen (Figure 1).

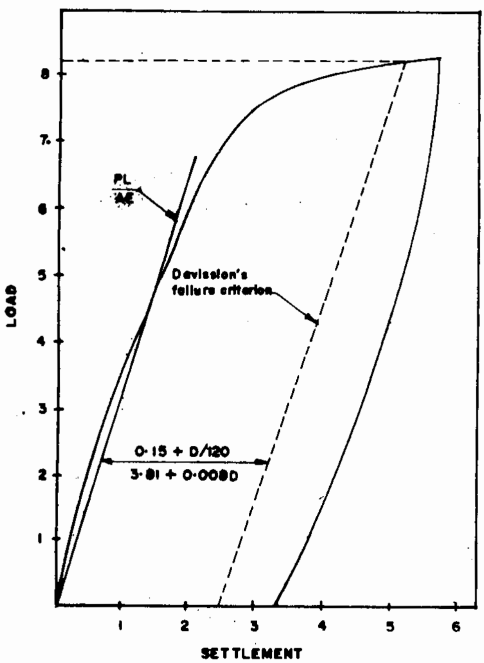


Fig 1. Static load load test results and interpretation (After Davission)

DYNAMIC METHOD OF MEASUREMENT AND ANALYSIS

Overview

Dynamic methods for evaluation of bearing capacity were used by early pile drivers centuries before the pile driving principles were recognized and understood. It was realized rationally that load carrying capacity of the pile would be higher when more effort was needed to advance a pile into the ground. Also it was intuitively clear that impacting a pile with an excessively large mass or drop height would most likely to cause pile damage externally or internally though the pile would advance faster. Engineers have tried to express the relationship between the effort needed to drive a pile and its bearing capacity in a simple formula (Hussein et.al., 1988) based on principles of Newtonian Physics pertaining to bodies of motion. Actually Newton himself warned against the use of his impact theory in pile drilling analysis (Terzaghi, 1943). This early dynamic approach was a crude analysis of the ram impact on a pile.

Early in the nineteen century, it was recognized that dynamics of pile driving can be better modeled by wave propagation rather than by idealized rigid body impacts. Mathematical closed-form solutions could not be deduced easily due to the complexity of the problem. The first measurements were taken during driving in 1938 in England as an attempt to better understand and control the pile stresses and soil resistance more pragmatically. In the 1950, the availability of digital computers made possible to have a discrete solution of elastic one dimensional wave propagation and thus computer programs were written (Smith, 1960). The type of analysis become known as the "wave equation". The method models hammer, pile and soil with a relatively high degree of realism. Results from wave equation analyses are widely used for assessing pile drivability and static bearing capacity during driving, or after installation with a restrike. Details pertaining to this type of analysis can be found in the literature (Goble et.al., 1976 and Hussein et al., 1988). The wave equation is an excellent analytical tool for a solution of a complex problem before going into the field. However, since the solution depends on assumptions, accurate stress or bearing capacity results with higher degree of accuracy, it can only be assessed through actual measurements of hammer and/or pile dynamic quantities occurring during blow of a hammer in the field.

Case Method

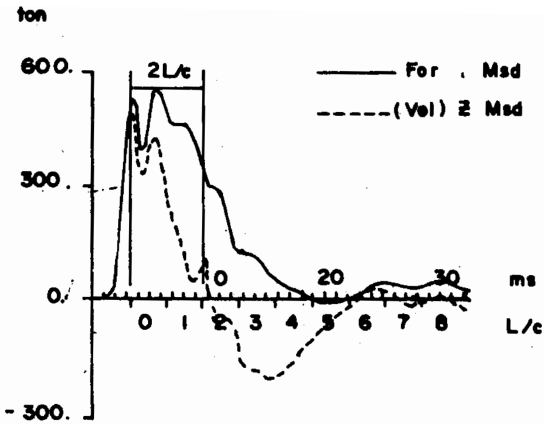
The technique of case method which is most widely used now-a-days for both measurement and field analysis of piles, were developed at Case Institute of Technology, Cleveland, Ohio under the direction of Professor G.G. Goble. The technique is therefore called the Case Method. The Case Method (Goble, 1975, and Goble et al., 1985) encompasses the measurement of force and velocity during a hammer blow and the computation of some 40 dynamic variables in real time by employing reusable strain transducers, piezoelectric accelerometers, and a Pile Driving Analyzer (PDA). The PDA is a data acquisition system and user-friendly field computer that provides power supply and signal conditioning for the transducers. It applies Case Method solutions to the measurement of data to calculate: (i) pile static bearing capacity, (ii) driving induced pile stress (compressive and tensile), (iii) hammer/driving system performance parameters, and (iv) a structural pile integrity related value. Required PDA inputs include pile length, cross sectional area, elastic modules, and density, specific calibration factors for the measuring gauges, and an assumption of a soil damping factor that represent soil dynamic behaviour under impact. It can be shown that using pile top records of force (F) and velocity (V) under a hammer impact on a uniform elastic pile, the total soil resistance (Goble et al., 1985) can be calculated from:

$$R = [F(t_1) + F(t_2) + \{V(t_1) + V(t_2)\} Z]/2 \qquad (1)$$

where, $t_2 = t_1 + 2L/c$, t_1 is a selected time during the hammer blow, Z is the pile impedance, equal to Mc/L (L is the pile length, M is the pile mass, and c the wave transmission speed related to material density and elastic modulus). The total resistance, R, is the sum of static, S (displacement dependent), and dynamic, D (velocity dependent) components. In order to find the static soil resistance S, the damping resistance D must be calculated and subtracted from R. The damping resistance D may be approximated by the product of a non-dimensionalized damping factor, J_c, and the calculated pile toe velocity.

$$S = R - (j_c)\,[F(t_1) + Zv(t_1) - R] \qquad (2)$$

The toe velocity times pile impedance is found from pile top force and velocity and resistance as shown in the right hand term of Equation 2. The damping factor, j_c, can be solved directly from the above equation if the failure load from a static load test is substituted for S. In this way, the damping factor was found to be related to the soil grain size. Originally, the Case Method capacity, S, was calculated at the time, t, of highest pile velocity with relatively sensitive damping factors. Presently, the time, t_1 is usually chosen such that it yields the maximum static resistance, i.e., at a time when the pile reaches the maximum temporary penetration and starts to rebound. Then the pile possesses low velocity and the calculated static resistance becomes insensitive to the choice of j_c. Figure 2 illustrates the data provided by the PDA and its Case Method interpretation to compute pile static capacity for a concrete pile.



$F(t_1)$	=	530 tons	$F(t_2)$	=	340 tons
$Zv(t_1)$	=	490 tons	$Zv(t_2)$	=	90 tons
R	=	$[F(t)+F(t2)+Zv(t_1)-Zv(t_2)]/2$			
	=	[530+340+490-90]/2=635 tons			
S	=	$R-j_c[(t_1)+Zv(t_1)-R]$			
	=	[635-(0.55) [530+490-635]			
	=	423 tons			

Fig 2. Example of Case Method Results.

The Case Pile Wave Analysis Program (CAPWAP)

CAPWAP (the Case Pile Wave Analysis Program) is a procedure which allows the computation of soil resistance forces and their distribution along with other dynamic soil parameters from measured force at pile top and velocity histories during a hammer blow (Cheong etal., 1991 and Tungsanga et al., 1989). The CAPWAP pile model consists of a series of segments of equal stress wave travel time corresponding to approximately 1 m length. The soil reaction forces are represented by passive, static (elastoplastic) and dynamic (linearly viscous) components, as originally proposed by Smith (1960). Such resistance forces act both along the shaft and below the pile tip. They can be calculated from pile displacement and velocity given at each segment, an ultimate static resistance and quake value (static components) and a dash pot constant (dynamic component). Note that ultimate resistance divided by quake yields the soil stiffness. The sum of all segment ultimate resistance values is the total ultimate capacity of the pile. At first, a complete set of assumptions (i.e., static capacity, quakes and damping at each pile segment) along with pile model are entered into the computer. A trial analysis is then made and one of the calculated pile top quantities is compared with the equivalent measured values. Additional trial analyses are then performed interactively by the engineer using a personal computer in an attempt to better approximate the measured values. The program can also obtain solutions "automatically" in its "experts system" mode. Case 1, 2, 3, 4 and 5 present case histories where a CAPWAP analysis on pile were used and the pile was also tested by static load tests. Comparison of results include ultimate static bearing capacity and pile top load movement relationship.

CASE STUDIES

All Dynamic load tests herein were conformed to ASTM 4945.

Case 1

600-mm. Precast Prestressed Concrete Spun Pile at Lot 4, km. 12+400-Yard II

A 600-mm prestressed concrete spun pile with a length of 28 m (14+14 m) and an area of 1,571 cm^2 was driven with a Hysinc hydraulic hammer (10 ton ram weight). The test pile was located next to PTT Building, north of Lad Phrao Flyover. For the initial drive, the 0.6 - 1.1 m drop height was utilized. Dynamic measurements were monitored during initial drive to the final penetration of 27.5 m. The soil condition can be described as a 10 m layer of soft clay under which a 14.5 m thick of medium stiff to stiff clay before reaching sand layer. The capacity from dynamic load test was 1.40 MN at the end of initial drive (EOID). Four days after installation, the dynamic load test was performed and the pile was restruck and had an ultimate pile capacity of 3.3 MN which represented a soil-pile set up of 1.90 MN (135%). The result of CAPWAP are presented in Figure 3. Since the contractor was unable to idealize his pile driving equipment to determine soil-pile set-up during restrike test. Therefore, the equipment was mobilized out from the job site and performed static load test having an ultimate pile capacity of 4.92 MN. Note that the Davisson's failure criterion was utilized to interprete the results of static load test and dynamic load test (CAPWAP). The results of static load test indicated that an ultimate capacity is increased by 1.62 MN, (49%) within 18 days after dynamic load test at the beginning of restrike was performed (Figure 4). The total soil-pile set-up capacity was also increased by 3.52 MN (251%) within 22 days after initial drive from dynamic measurements.

Case 2

800-mm. Precast Prestressed Concrete Spun Pile at Lot 6, Pier 6.30.

A 800-mm prestressed concrete spun pile having a length of 29 m and an area of 2,564 cm^2 was driven with a Hysinc hydraulic hammer (12.5 tons ram weight, 0.3-1.2 m. stroke) and encountered a resistance of 15.8 mm. per blow for the last 3 m. High Strain dynamic measurements were made during initial drive and restrike six and eleven days after pile installation. The subsurface conditions can be described as various layers of soft clay, stiff clay and dense sand material. Analysis according to the CAPWAP method was performed on data during the initial and restrike tests. Results and comparison between static and dynamic load tests performed on the sample are shown in Figure 5. CAPWAP computed an ultimate pile capacity of 2.3 MN during initial drive and 7.4 MN and 8.1 MN during restrike at 6 days and 11 days after initial drive, respectively. The soil pile set-up presented a good correlation when compared with the static load test as shown in Figure 5.

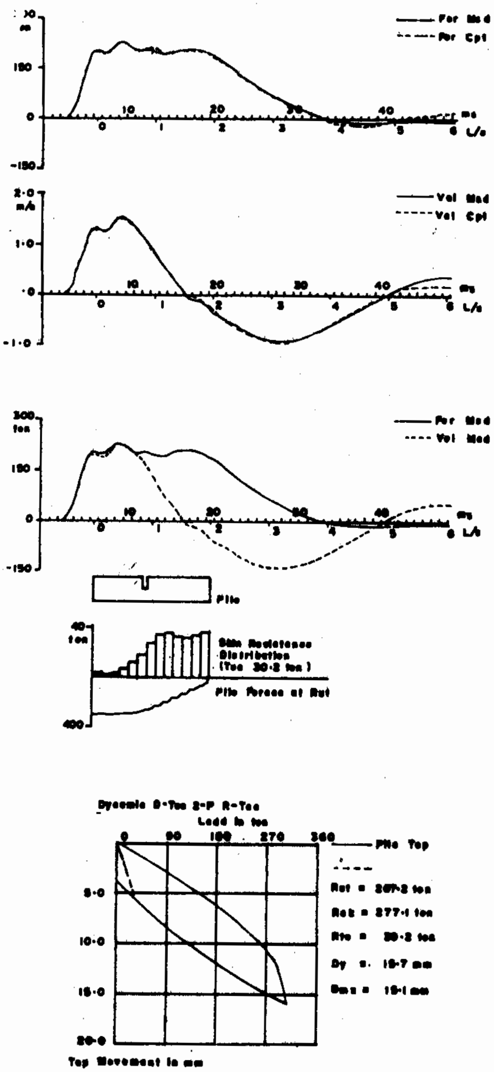


Fig 3. CAPWAP Analysis Results, Case 1

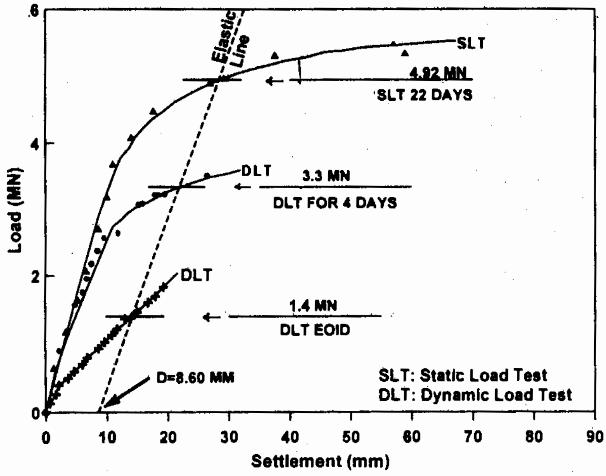


Fig 4. Comparison of Static Load Test and Dynamic Load Tests (Case 1)

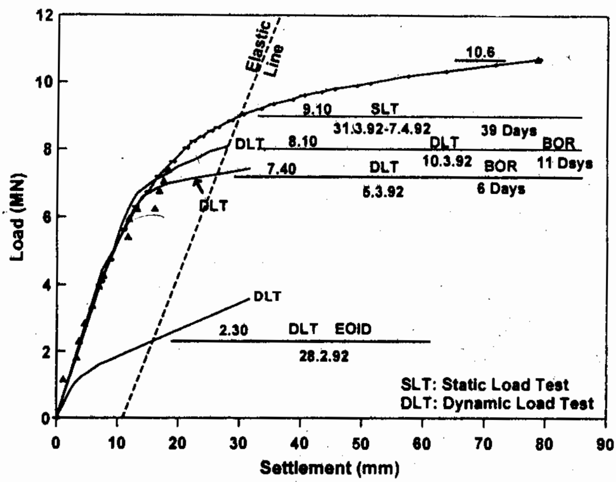


Fig 5. Comparison of Static Load Test and Dynamic Load Tests (Case 2)

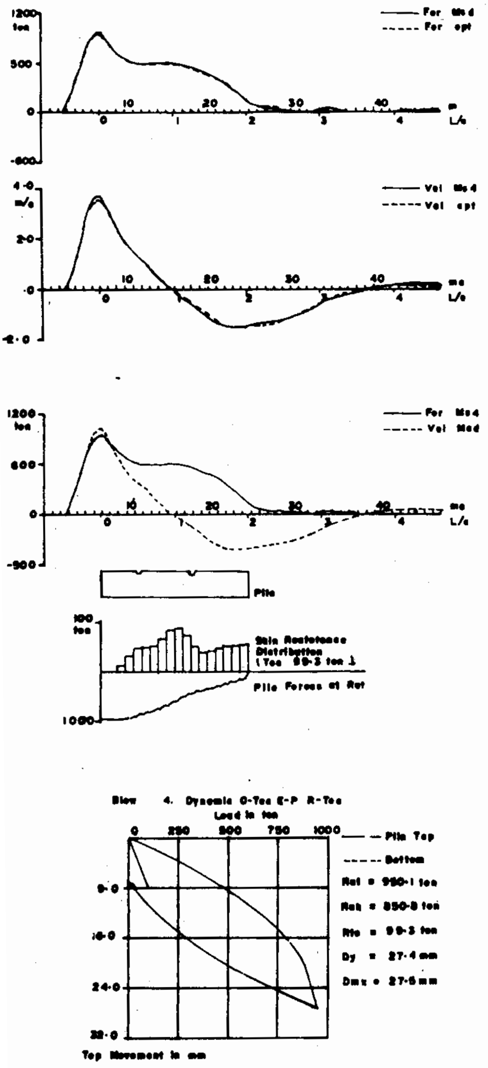


Fig 6. CAPWAP Analysis Results (Case 3)

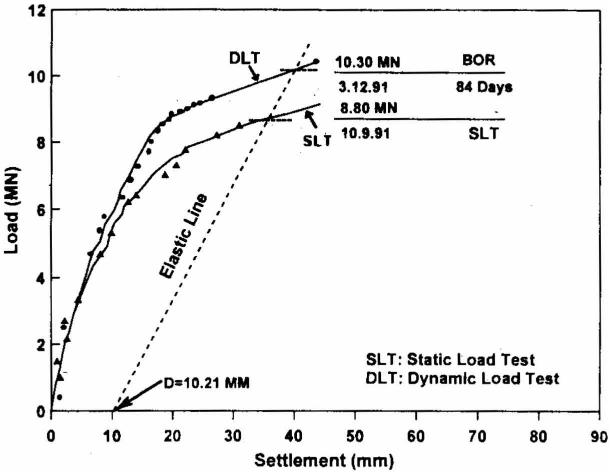


Fig 7. Comparison of Static Load Test and Dynamic Load Tests (Case 3)

Case 3

800-mm Precast Prestressed Concrete Spun Pile at Lot 6, TP4.

A 800-mm precast prestressed concrete spun pile with a length of 38 m (13+13+13 m.). Test pile TP4 was located near Yakult Co., Ltd. TP4 was initially driven with a Hysinc hydraulic hammer (12.5 ton ram weight, 0.2-1.2 m stroke) through first sand layer into stiff clay and a resistance of 24 blows per 30 cm. Static load test was performed on this pile after 72 days from initial installation and presented an ultimate pile capacity of 8.8 MN. The pile was then subjected to a restrike with the modified driving system using 15 ton steel drop weight and a drop height of 4 m and was dynamically instrumented on this pile after 84 days from static load test. Analysis according to the CAPWAP method was performed on data during the restrike test. Results from CAPWAP include (Figure 6): measured pile top force and velocity records (first and second from top), both soil resistance distribution and pile forces along the shaft at ultimate capacity (second from bottom) and a statically calculated load-set curve based on CAPWAP's predicted resistance and quake values (bottom). Furthermore, for each pile segment, ultimate static soil resistance, (until friction and unit end bearing values), soil quake and damping factors. A dynamic analysis performed on this restrike data computed a pile ultimate static capacity of 10.3 MN as shown in Figure 7.

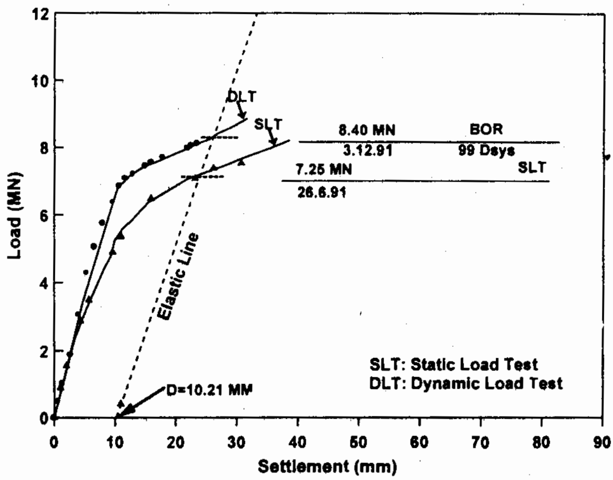


Fig 8. Comparison of Static Load Test and Dynamic Load Tests (Case 4)

Case 4:

800-mm Precast Prestressed Concrete Spun Pile at Lot 6, TP3.

A 800 mm prestressed concrete spun pile with a length of 25 m final (penetration of 24.6 m.) was driven with a Hysinc hydraulic hammer (12.5-ton ram weight, 0.2 - 1.2 m stroke). TP3 was located near Yakult Co., Ltd. Soil conditions consisted of soft clay to a depth of 18 m under which lies medium dense, fine to coarse sand. Static load test was performed on this pile and indicated a pile ultimate capacity of 7.25 MN. After 99 days, dynamic load test was performed utilizing a modified 15-ton steel ram weight and a drop height of 3 m to mobilize the pile toe. The dynamic data from each blow was also analyzed with the CAPWAP program. According to CAPWAP analysis (Figure 8), the ultimate static pile capacity is 8.4 MN. The static load displacement response of the pile, predicted from dynamic measurements, is in good agreement with the actual behaviour.

Case 5

800-mm Precast Prestressed Concrete Spun Pile at Lot 3, TP2.

A 800-mm precast prestressed concrete spun pile with a length of 30 m. (final penetration of 29.4.). Test pile TP2 was located near St. John College, East of Lad Phrao Flyover TP2 was initially driven with a Hysinc hydraulic hammer (12.5 ton ram weight, 0.3 - 1.2 m stoke). The subsurface conditions consist of various layers of soft clay, stiff clay and dense sand material at the depth of 23.8 m. Dynamic testing was performed as an initial drive having a resistance of 9.9 mm per blow for the last 1 m or 32 blows per 30 cm. Dynamic measurements and analyses performed for the end of driving indicated a pile capacity of 2.3 MN using Davisson's Criteria. The pile was instrumented and restruck 5 days later and CAPWAP analyses performed on data for the beginning of restrike computed an ultimate pile static capacity of 6.3 MN and present an increased capacity of 4 MN (174%) due to soil-pile set-up. A static load test performed on this pile indicated an ultimate static capacity of 10.25 MN which presented a soil-pile setup capacity of 7.96 MN (346%) after 32 days from initial pile installation. The dynamic measurement presented a good correlation with static load test. Figure 9 shows the soil resistance which increases with time due to soil strength "set-up".

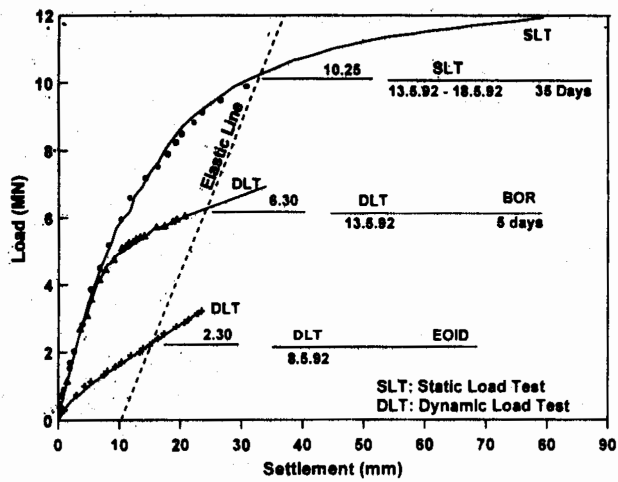


Fig 9. Comparison of Static Load Test and Dynamic Load Tests (Case 5)

CONCLUSION

The research study shows that carefully executed static load test is the most reliable means of determination and verification of bearing capacity of pile foundation. However, they have time and cost constraint and sometimes become difficult to execute which severely limit their pragmatic application in many cases. The comparative study of data and results shows that dynamic testing provides a viable alternative that also furnishes additional information regarding performance of the total hammer pile-soil system. This types of testing is equally applicable to driven as well as bored piles. The five case histories presented in this paper show a close correlation of pile capacity calculated from static and dynamic tests. The five tests presenting good correlation can be expected in most soil types if restrikes are performed and pile sets are sufficiently large to activate the full soil resistance.

ACKNOWLEDGMENTS

The authors would like to express their gratitude to Mr. Garhard Laber, Dywidag Consortium J.V., Khun Kiart Chuanromance, Business Development Manager, Don Muang Tollway Co., Ltd. and Khun boonchuan Limisila, project Manager, Department of Highways, Ministry of Transport and Communications, Thailand for their help and cooperation they rendered in this research study.

REFERENCES

American Society for Testing and Materials, (1989), ASTM D4945-Standard Test Method for High-Strain Dynamic Testing of Piles, Philadelphia.

Cheong, K.L., and Tungsanga, K., (1991), "Evaluation of Bearing Capacity and Performance of Pile Using Stress Wave Measurements (Dynamic Load Test)", The Engineering Technology Symposium, Engineering Institute of Thailand, pp. 501-539.

Edde, R.D. and Fellenius, B.H., (1990), "Static or Dynamic Test. Which to Trust?", Geotechnical News, Vol. 8., p. 28, Vancouver, British Columbia.

Fellenius, B.H., (1980), The analysis of Results from Routine Pile Load Tests, Ground Engineering.

Goble, G.G. (1975) "Bearing Capacity of Piles from Dynamic Measurements - Final Reports", Dept. of Civil Engineering, Case Western Reserve University, Cleveland, Ohio.

Goble, G.G. and Rausche, F., (1976), "Wave Equation Analysis of Pile Driving-WEAP Program", Vol. 1-4, FHWA, IP 76-13, 1-IP-76-14.4.

Goble, G.G., Likins, G.E. and Rausche, F., (1985), "Dynamic Determination of Pile Capacity," Journal of Geotechnical Engineering, ASCE, pp. 367-383.

Hussein, M., Likins, G.E., and Rausche, F., (1988), "Wave Equation Analysis of Pile Driving Methodology and Performance", Sixth National Conference on Micro-Computers in Civil Engineering, ASCE, pp. 80-85.

Smith, A.E.L., (1960), "Pile Driving Analysis by the Wave Equation", Journal of Soil Mechanics and Foundations, ASCE, pp. 36-61.

Terzaghi, K., (1943) "Theroretical Soil Mechanics," John Wiley and Sons, New York, p. 150.

Tungsanga, K., (1989), "Pile Capacity Testing Using Dynamic Load Test", The Techincal Conference, Engineering Institute of Tahiland, pp. 608-628.