STATIC AND HIGH STRAIN DYNAMIC TEST CO-RELATION STUDIES ON CAST-IN-SITU CONCRETE BORED PILES

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SYNOPSIS

Maharashtra State Road Development Corporation Ltd., has initiated a scheme for construction of 55 flyovers in Mumbai in India. To ensure speedier completion of projects several new technologies were adopted to save time without compromising on safety and reliability. Many of the flyovers involved large diameter pile foundations carrying loads ranging from 3500kN to 1375kN. Significant time would have been lost in using conventional load testing procedure to check pile capacity apart from the difficulty in mobilizing the load and the obstruction to site movement and traffic on the adjoining roads. High Strain Dynamic Testing was introduced on the project sites in lieu of static load testing after conducting numerous co-relation studies on various project sites. A total of seven co-relation studies have been conducted till date and based on these data static testing has been replaced by dynamic testing on numerous flyovers. The paper presents the results of such studies. CAPWAP analysis was also conducted on the data to evaluate the percent skin friction and end bearing so as to improve future design parameters.

1.0 INTRODUCTION

In India, Maharashtra State Road Development Corporation has initiated a scheme for 55 flyovers to be built across various junctions at city points to ensure smooth flow of traffic. Pile foundations have been used on various flyover projects to transfer superstructure loads to the underlying strata. This has also increased the need to ensure that the foundation is safely installed. Thus as a part of standard quality control 2% of the piles on each flyover were to be statically tested. The usual method used here was to evaluate pile quality and capacity was by a static load test, which involved physically loading the pile with the test load and check the net and total settlements under the load. The method was found to be time consuming and rarely are complete details obtained from the test. Further, it resulted in significant obstruction to site movement and traffic on adjoining roads. Thus a pile close to traffic intersection was difficult to test. High Strain dynamic and pile integrity tests have been used during the last few years to evaluate pile quality and/or capacity, but the use of such testing has been limited due to absence of proper test data and confidence in this form of testing.

The results of High Strain Dynamic tests were hence first co-related to static tests by subjecting the pile both to static testing and dynamic testing. Based on satisfactory match of the results, dynamic testing was adopted on the project sites. The paper also describes the principle and procedure involved in dynamic pile testing and presents the methodology and results for testing on bored piles on various flyover projects. The collected data was also subjected to

*** Proceedings of “Deep Foundation Institute 2000”, New York, USA, September 2000**

CAPWAP™ (Case Pile Wave Analysis Program) the use of which is relatively new here to evaluate the soil and pile parameters including skin friction, end bearing, cross-sectional profile etc. A typical analysis for one of the projects is attached. Data collection was conducted using a Pile Driving Analyzer – Model PAK (PDA) obtained from Pile Dynamics Inc., USA.

2.0 PRINCIPLE OF HIGH STRAIN DYNAMIC PILE TESTING

The basic purpose of dynamic testing is to evaluate pile capacity and structural integrity of the pile and the total settlement under the measured capacity. Strains are recorded by the Pile Driving Analyzer™ with the help of strain transducers attached to the pile, whereas accelerometers record the accelerations generated in the pile caused due to the impact of a heavy hammer falling from a pre determined height. The PDA converts strain to force, and acceleration records are converted to velocities. The resistance developed by the pile is then a function of force and velocity and includes few assumed factors such as the quake and damping parameters as inputs based on the soil type. A more accurate value of these parameters is then obtained from CAPWAP analysis conducted on field data. Further discussion is beyond the scope of the paper. Field results usually includes capacity of the pile, based on an assumed damping value, stresses in the pile, net settlement and total settlement of the pile, skin friction, end bearing, etc., although 30 different parameters are evaluated.

3.0 CAPWAP ANALYSIS

The CAPWAP program is an analytical method that combines measured field data with pile wave equation type procedures, to predict the pile's static bearing capacity and soil resistance distribution. Measured force and velocity data is directly input from the PDA. Based on the measured velocity data, the program computes the force required to induce the imposed velocity. Both measured and computed forces are plotted as a function of time and the iterative analysis is continued till there is good agreement between both the curves. If the agreement is not satisfactory, the soil resistances at the pile point and along the pile are adjusted until a good match is obtained. This gives the frictional distribution along the sides, the end bearing component of the pile, as well as better estimates of the actual static pile capacity measured during field testing.

4.0 METHOD OF TESTING

The method involves attaching strain transducers and accelerometers to the sides of the pile approximately 1.5 times pile dia. below the pile top. A pair of transducers is fixed onto opposite sides of the pile so as to detect bending in the pile if any during testing. These transducers are then connected through the main cable to a Pile Driving Analyzer - MODEL PAK, which is a State of Art Pentium Computer System with ability to record strain and acceleration measurements and convert them from analog to digital form. The signals are then triggered by the impact of a ram falling from a pre-determined height. The ram weight and fall height is determined in advance. As a thumb rule, the ram weight shall be 1-2% of the testing capacity of the pile. For case histories described below, hammer weight equal to 1% of test capacity was used and the drop height varied from 1m to 3m. A 25mm thick plywood cushion and 16mm thick steel plate were placed on the pile top to avoid any damage to the pile during testing. The testing procedure as per ASTM D4945 in general was followed. The following describes in brief individual case studies on each flyover.

CASE STUDY 1

SION & KURLA FLYOVER PROJECT

This was the first flyover on which a co-relation study was conducted to establish reliability of dynamic testing. Pile No. 14-L was initially subjected to a conventional static load test with concrete blocks. The pile was 1200mm in diameter and was 22.5m length from ground level. The pile penetration was 20.8m with a working load of 3393kNand a test load of 5090kN. Casing was used till soft rock level. Static load testing on the pile for a load of 5150kN revealed a settlement of 2.7mm. Dynamic testing was conducted on the pile immediately on completion of static testing. The pile was impacted with a 60kN hammer falling from a height of 2m. The capacity was obtained from CAPWAP analysis of force and velocity curves measured inside the PDA. The results of dynamic testing showed a settlement of 2.34mm under a load of 5150kN. The compressive stress recorded in the pile was found to be 5.88N/mm^2, and can be termed as within limits. The integrity factor was 100% indicating good structural integrity. The load settlement curves for both the forms of testing are presented in Figure:1. It can be seen that variation in results between both the tests is only 0.34mm. This was termed as acceptable and it was decided to substitute dynamic pile testing on the above mentioned project site in lieu of static load testing. A total of 7 piles were later subjected to dynamic testing on this flyover site with satisfactory results.

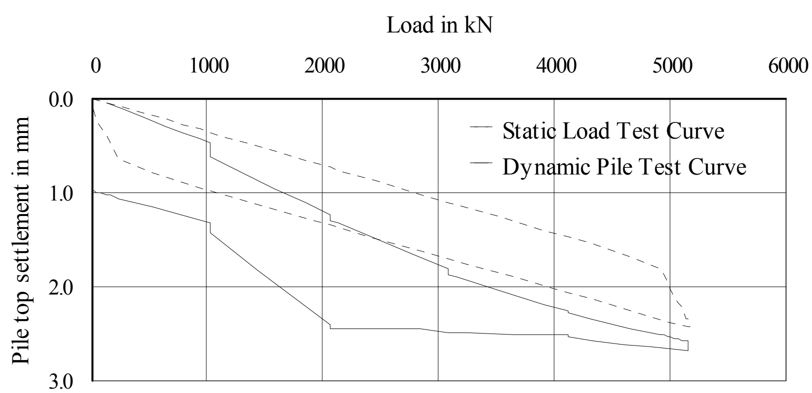

Figure 1 Pile No. 14-L at Kurla Flyover, Mumbai
Static Test:12/09/98 ; Dynamic Test 28/09/98

CASE STUDY : 2

FLYOVER AT BORIVALI NATIONAL PARK

Two piles were tested both statically and dynamically to establish the reliability of the tests. The piles were 1m in diameter with a working load of 2350kN and test load of 3525kN. Pile No. P4-6 was subjected to a high strain dynamic test. The test was conducted using a 32kN hammer falling from a height of 2.0m. Although usual practice is to conduct dynamic test after completion of static testing, at the request of the consultants for this site, dynamic testing was conducted prior to site. Their purpose of doing static test later was to ensure that the results of such testing is not known in advance so as to remove any doubts about the test method. High strain dynamic testing on the pile showed a pile top settlement of 1.301mm at a capacity of 3530kN, although actual pile capacity is higher as seen from the curve. Conventional static test results showed a settlement of 0.913mm under equivalent load. Thus the difference between both the results was only 0.38mm. Again since the pile had already undergone some net settlement under high strain test, the net settlement was almost negligible under repetitive loading. Refer to Figure:2 for details about co-relation curve.

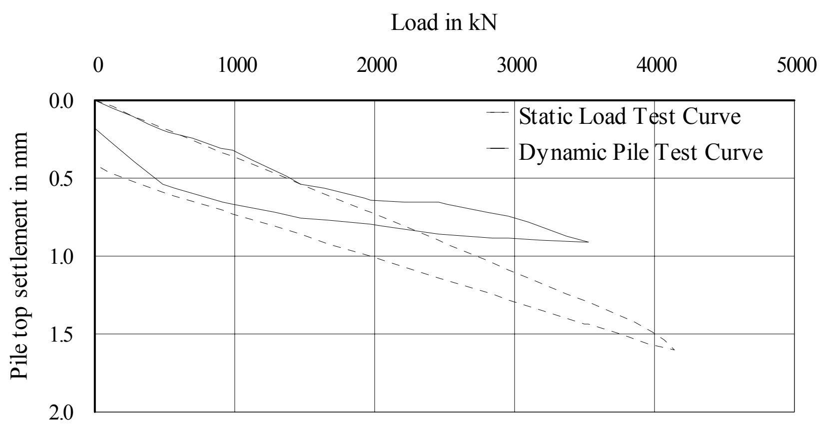

Figure 2 Pile No. P4-6 at National Park Flyover, Mumbai
Dynamic Test: 23/05/99; Static Test: 15/07/99

Another Pile, No. P13-8 was also tested statically first and then subjected to high strain dynamic testing. This ensured that the high strain test method is checked comprehensively. A heavier hammer of 43kN with a fall height of 1.5m was used in this case. This reduced the drop height and made the impact more effective. The test capacity was similar to Pile No. P4-6. The difference in both the test results in this case was as 0.228mm. The co-relation study for both the tests is attached in Figure:3. Based on two such co-relation results, future testing on site was conducted using high strain dynamic testing.

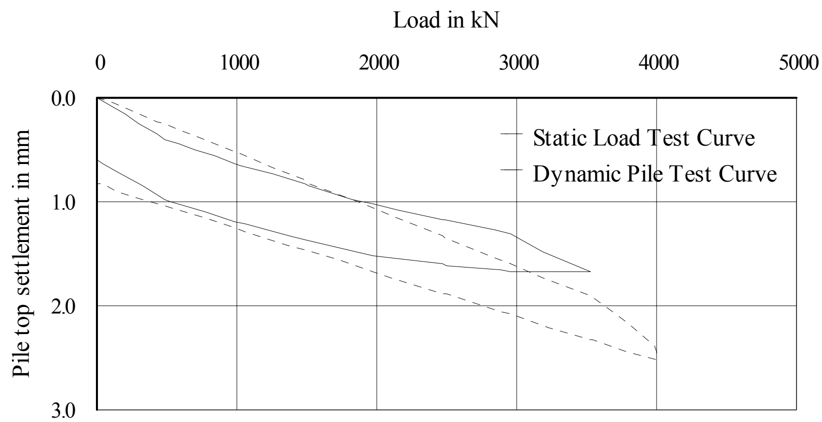

Figure 3 Pile No. P13-8 at National Park Flyover, Mumbai
Static Test: 07/08/99; Dynamic Test 02/09/99

CASE STUDY NO. 3

VAKOLA FLYOVER PROJECT

This particular flyover was 1.8km long and covered two junctions. A total of 10 piles were to be tested statically on site. As decided by the project management consultants on site, it was decided to test an initial pile both statically and dynamically. It was also decided to test two routine piles statically and two adjoining piles in the same group with high strain dynamic test. This was to negate any settlement that may have occurred during static or dynamic testing, depending on whichever is carried out first.

An initial pile of 600mm was subjected to static load test first. The maximum applied pile test load was only 1770kN. Static test results for the pile showed a settlement of 1.386mm with an elastic response. The pile was not loaded to failure but only to 2.5times the design load. High strain dynamic testing results for the pile showed a settlement of 1.21mm under equivalent capacity. It was also observed that the pile had significantly higher capacity that was not mobilized during conventional load test. A 30kN hammer falling from a height of 2m was used. This resulted in substantially higher energies being transferred to the pile resulting in higher capacity. Refer to Figure:4 for the co-relation study for 600mm diameter pile.

Since the underlying stratum was suspected to be relatively soft rock, two additional co-relation studies were also conducted by statically and dynamically loading adjoining piles. The results of these tests were also found to be satisfactory.

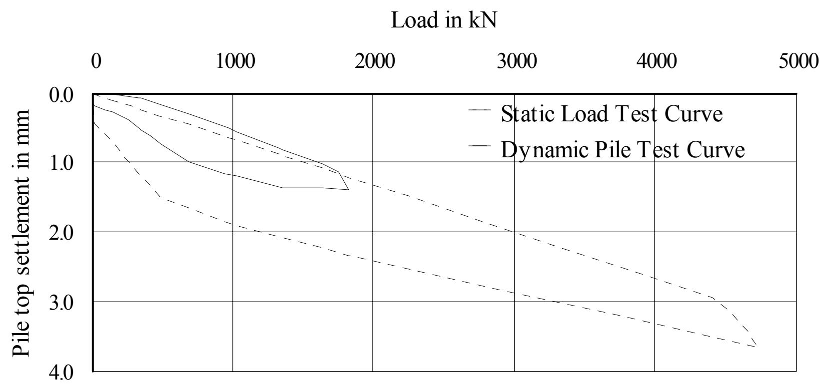

Figure 4 Initial Test Pile at Vakola Flyover, Mumbai
Static Test:20/01/99; Dynamic Test: 24/04/99

CASE STUDY 4

URBAN VIADUCT FROM JJ HOSPITAL TO PALTON ROAD FLYOVER

The project management consultants for this flyover approved the use of dynamic testing on flyover sites largely due to the fact that previous data was available. Maharashtra State Road Development Corporation also agreed to include dynamic testing in the specifications due to fair amount of confidence developed in this form of testing. It was also decided to conduct similar studies on this flyover also and compare the results. Eventually atleast 15 piles are planned to be tested dynamically.

The pile in consideration was an initial pile of 1200mm in diameter with an ultimate capacity of 13750kN. Due to better rock strata as compared to other sites, it was possible to increase the design capacity for the same pile diameter. Concrete grade was G35 (35N/mm^2) and was ready mix concrete. The soil strata consisted of stiff soil till 3m from top and soft rock from 3m onwards. The pile was socketed into rock up to at least 3 times of pile diameter. Static testing of the pile to 13750kN was conducted using pre-stressed rock anchors, since a conventional load test was very difficult. The static test results showed a settlement of 4.012mm under the test load.

Dynamic testing also presented a difficult task, since it was necessary to design and fabricate a hammer capable of mobilizing a capacity of 13750kN. At 1% of the test capacity a hammer of 140kN was required. It was also required to keep the volume of hammer as minimum as possible to get better impact. The contractor fabricated the hammer onsite in consultation with the test agency. This was the first time that such a heavy hammer was fabricated in India specifically for dynamic testing.

High Strain Dynamic Testing was conducted on the pile by impacting the pile from a height of 2.0m. The CAPWAP analysis conducted on the pile indicated a capacity of 14000kN under the impact and the total pile impact and total pile settlement of 2.6mm. The net settlement during the test was almost zero. This was as per expectation, since the pile had already undergone some settlement under static loading. Thus comparison of pile top movement of both the tests showed very good agreement even for heavier capacity. Refer to Figure:5 for the correlation study.

A complete CAPWAP analysis was also conducted on the pile to evaluate skin friction and end bearing components. The abridged results are presented in Table:1. Although the pile was designed as end bearing, significant capacity contribution of upto 11370kN was obtained due to skin friction. The mobilized end-bearing component was 2620kN. The analysis also shows that capacity contribution upto 3m from top was 3350kN. Maximum contribution was in the region from 2.9m to 4.9m from sensor level. This is also the region where there is presence of rock. The friction component observed from 4.9m to 6.9m was 3545kN and is lesser than the upper crust.

The case damping factors for skin and toe are also fairly high at 1.2 and 1.0. All this probably indicates that full capacity is not yet mobilized, and the pile still can withstand higher resistance than the designed ultimate capacity. The test results were found to match fairly well in as in previous cases. Based on these results and another such study that is yet to be conducted, the clients and the project management consultants are planning to adopt dynamic testing on the flyover site the work for which has just begun.

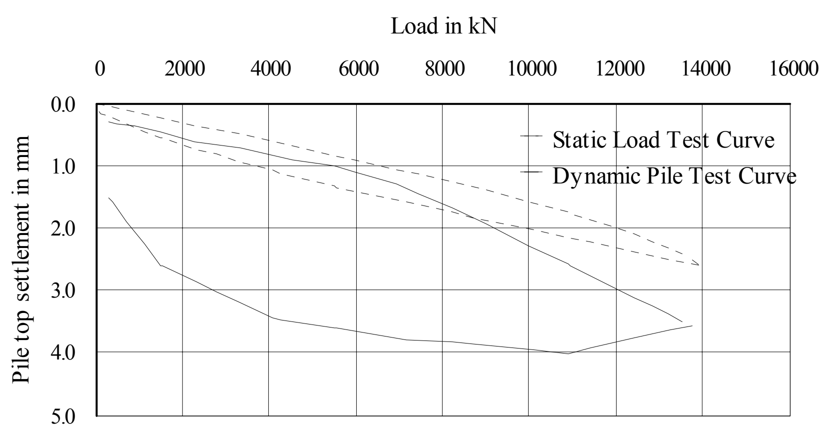

Figure 5 Initial Test Pile at JJ Urban Viaduct, Mumbai
Static Test: 14/05/99 ; Dynamic Test 21/05/99

CAPWAP FINAL RESULTS

Total CAPWAP Capacity: 14000.0; along Shaft 11371.4; at Toe 2628.6 kN

Soil Sgmnt No.	Dist. Below Gages m	Depth Below Grade m	Ru kN	Force in Pile at Ru kN	Sum of Ru kN	Unit Resist. w. Respect to Depth kN/m	Unit Resist. w. Respect to Area kPa	Smith Damping Factor s/m	Quake mm
				14000.0					
1	3.0	2.9	3359.1	10640.9	3359.1	1679.53	445.50	1.159	.750
2	5.0	4.9	4466.5	6174.4	7825.6	2233.26	592.38	1.159	.750
3	7.0	6.9	3545.8	2628.6	11371.4	1772.91	470.27	1.159	.750
Average Skin Values			3790.5			1648.03	502.71	1.159	.750
Toe			2628.6				2324.14	4.179	.850

Soil Model Parameters/Extensions	Skin	Toe
Case Damping Factor	1.200	1.000
Unloading Quake (% of loading quake)	100	82
Reloading Level (% of Ru)	100	0
Unloading Level (% of Ru)	0	
Soil Plug Weight (kN)		120.00

Table 1

5.0 REVIEW OF HIGH STRAIN DYNAMIC TEST RESULTS

1. Several piles were subjected to static and dynamic testing to evaluate the reliability of the test method before adopting it in the specifications and also allowing its use on many flyover sites. (Results of 5 tests are published here, and other tests also gave similar results). The pile diameters varied from 600mm to 1200mm and capacities ranging from 1770kN to 13750kN. The pile lengths also varied from 6m to 20m approximately.

2. It can be said that there was good agreement in all the cases. The relevant project management consultants on site were to monitor the test and adopt it once the results were found to be satisfactory. Their view was also taken into consideration before adopting the test method on the site.

3. These were the first such studies conducted in India on this magnitude with the co- operation of contractors/consultants/ and test agency under overall client monitoring.

6.0 CONCLUSION

1. On the basis of above findings, it can be concluded that High Strain dynamic pile testing was found to be fairly reliable to evaluate pile capacity.

2. The method is significantly faster than an equivalent static load test. The use of concrete blocks which was very time consuming and cumbersome is avoided.

3. Further several piles can be dynamically tested in one day resulting in considerable savings of time, and early completion of the project.

4. Dynamic pile testing avoided the problem of availability of space for other site movement and construction. It was possible to also test piles that were very close to the road traffic, which otherwise would have been impossible with a static test.

5. Structural integrity of the pile is also verified. It is also possible to evaluate the skin friction and end bearing component of the pile if required.

6. Data generated proves that dynamic testing can be adopted on project sites in the region and elsewhere. It is expected that this method of testing will find increased use in construction in India and the region due to above benefits.

7. LIMITATIONS

1. Unlike static testing, evaluation of dynamic pile test results requires an experienced engineer trained in interpretations of the results. Interpretations carried out by persons not fully trained for use of PDA can result in serious errors on site and can also lead to delay of site work and various complications.

2. Hence more such co-relations between dynamic and static testing should be encourage under different types of soil, before the method can be widely adopted on other sites. This also helps evaluating the reliability of test agency hired to do the test.

3. Large diameter bored piles are still relatively new in Indian industry. Eventually as pile load capacity increases, it may be difficult to fabricate heavier hammers and design fall mechanisms. Recently many countries have reported using the PDA to measure pile capacity upto 50000kN and this should solve any problems associated with drop weight or mechanisms.

8.0 REFERENCES

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