High strain dynamic pile load test at Delhi Metro Rail project

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The Delhi Metro Rail project is being undertaken in the city. Its project execution is challenging as construction is to be undertaken in congested parts without disrupting traffic. In this paper, the authors present details of the high strain dynamic test which was undertaken to save time.

Delhi Metro Rail project is being designed and constructed as a world class metro rail system. The construction of the metro rail transport system (MRTS), having a length of about 200 km, will be completed by the year 2021. Delhi MRTS Phase – I is currently under implementation. The paper describes the pile load test carried out using high strain dynamic test conducted in elevated rail corridor between Trinagar to Rithala. The section between Trinagar to Rithala involves construction of around 1700 numbers of 1500-mm diameter bored cast-in-situ piles. There were significance changes in the stratum of the above stretches, a typical bore log can be seen from *Table* 1. Therefore designers have recommended pile load test — both initial load test and routine load tests — to ascertain load carrying capacity of the piles. As the entire project execution was carried out in highly inhabitated area and under heavy traffic congestion, it was difficult to adopt conventional method of testing of piles, both in terms of availability of space and also time constraint. Under the circumstances the project authorities had to look for new technology/alternate methods of testing these piles and save time. After exploring various possibilities and reliabilities of testing the piles, it was decided to test the piles using "Pile Dynamic Analyser" (PDA) subject to satisfactory co-relation between static and dynamic load test results. Number of co-relation studies were carried out at different soil conditions. These results are discussed in this paper.

The results of high strain dynamic tests were co-related with static test by conducting tests — both static and dynamic tests. The paper also describes the principle and procedure involved in dynamic pile testing and the methodology and results for testing of bored piles. The collection data was subjected to *CAPWAP* (Case Pile Wave Analysis Program) analysis. The use of such analysis is relatively new in India to evaluate the soil and pile parameters such as skin friction, end bearings, cross sectional profile, etc. The typical analysis of such tests is also furnished. The data collection was conducted using the *PDA – Model PAK* obtained from Pile Dynamic Inc., USA.

Principle of high strain dynamic pile testing

The basic purpose of dynamic testing is to evaluate pile capacity, structural integrity of the pile and the total settlement under the measured loading. Strains are recorded by the *PDA*™ with the help of strain transducers attached to the pile, whereas accelerometers record the accelerations generated

Table 1: Soil bore log details

Description of strata	*Depth, m*	
	From	*To*
Filled up soil	GL	0.5
Silty clay	0.50	6.00
Silty sand	6.00	12.00
Silty sand with kankar	12.00	14.00
Silty clay with kankar	14.00	15.00
Fine sand	15.00	22.00
Silty clay with kankar	22.00	25.00
Silty sand	25.00	26.50
Sandy silt with clay	26.50	30.50

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 thus becomes 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. Field results usually include capacity of the pile, based on an assumed damping value, stresses in the pile, net and total settlement of the pile, skin friction, end bearing, etc.

Structural details of piles

The typical structural details of the piles were as given below.

Grade of concrete	:	M35
Pile diameter	:	1500 mm
Design load	:	450 t
Average depth	:	29.0 m
Type of piles	:	Friction cum end bearing piles

Method statement for dynamic pile testing

High strain dynamic pile testing with the help of *PDA* is a reliable and proven method to evaluate the pile capacity and integrity for bored and driven shafts. The test replaces or supplements conventional static load testing. It consists of impacting the pile with a hammer whose weight is 1-1.5 percent of the test load and measuring the relevant forces and velocities. Information obtained from the test is considerably more than the one obtained from static testing. The test can be used to evaluate various pile parameters, important amongst which are mentioned below.

- True static capacity of the pile at the time of testing.
- Simulated static load test curve
- Total skin friction and end bearing capacity of the pile
- Skin friction variation along the length of the pile
- Compressive and tensile stresses developed in the pile during testing
- Net and total displacement of the pile
- Pile integrity and changes in cross-section if any.

The test is standardised as per ASTM D4945 and various other codal provisions worldwide.

Equipment

The equipment used is the *PDA – Model PAK* — manufactured by Pile Dynamics, Inc. This is the latest equipment which has been used in 30 countries across six continents. It is reported that this equipment is used more than any other similar equipment.

Hardware

Following are the hardware required:

- pile driving analyser – *Model PAK*
- strain sensors (2 numbers)
- acceleration sensors (2 numbers — also called accelerometers)
- junction cable and main cable
- fasteners for fixing sensors into concrete.

Software

Following are the software required:

- *PDA* software
- *CAPWAP* analysis software.

The softwares are patented by Pile Dynamics, Inc.

Site preparation

Pile built-up

The pile top needs to be re-built for a maximum length equal to 1 to 1.5 times the pile diameter with a minimum of 4-mm thick steel casing to provide smooth finish. This was done by extending reinforcement in built-up portion. Two openings/ windows (225 mm × 225 mm) diametrically opposite to each other need to be made if casing is used. This was for fixing gauges to the pile. The opening was located at a distance of about 1 to 1.5 times the pile diameter below the pile top.

Test preparation

A 40-mm thick plywood cushion with diameter equal to pile diameter was kept ready at the time of testing. Steel helmet, at least 50 mm thick, and with diameter equal to diameter of pile was also kept ready at the time of testing. The helmet shall not be welded to the pile casing. The plywood cushion shall be placed onto the pile head and the helmet was placed onto the top of plywood cushion. The purpose of using such an arrangement was to avoid damage to the pile head and ensure transfer of smooth wave into the pile. A 220-V single phase power supply was also provided near the pile.

A hammer of 6.5 to 7.5 t was used to test the pile to its test capacity of 450-t. A crane capable of lifting this hammer by its single line was also made available on site. The hammer was lifted by the crane and an impact ranging from 1m to a maximum of 3 m shall be applied onto the pile head. The actual height of fall was determined based on site results and pile test capacity.

Testing method

The dynamic test was conducted in accordance with ASTM D4945. As prescribed, it was conducted 10 days after pile installation.

The following information was made available to the test agency prior to commencement of testing.

- Pile reference and location
- Pile length from test level
- Pile cutoff level, pile diameter
- Pile installation record that includes concrete grade, concrete consumption, etc

- Soil bore log
- Static test results, if any, in adjoining area
- Any other related information with respect to the piles to be tested.

Data collection

Dynamic pile testing (high strain testing) was conducted by attaching strain transducers and accelerometers to the sides of the pile approximately 1 to 1.5 times the pile diameter below the pile top. This pair of transducers was 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 the PAD – model PAK, with ability to record strain and acceleration measurements and convert them from analog to digital form.

The signals were then triggered by the impact of 6.5 to 7.5 t hammer falling from a pre-determined height. It is customary to start with a fall height of 1m and monitor the results before increasing drop height. Drop height was increased in phases of 0.5 m to monitor the capacity and settlement. The test was stopped once the required capacity is reached. If the pile started to settle more than 3-4 mm per blow before it reached its required capacity, then it was termed as failure load and the pile can take no further load. Normally the drop height was not be more than 2.5 m to 3 m and 3-4 blows were sufficient for one test.

The following input data was entered into the PDA test system before starting testing.

- Project name and pile no.
- Pile length from sensor level
- Pile length from ground level
- Pile area and wave speed
- Damping *Jc* = 0.5

Upon impact, the strain transducers measured strains whereas accelerations were measured by accelerometers connected on either sides of the pile. These signals were then converted to digital form by the PDA software and then converted to force and velocity, respectively, by integration.

The capacity mobilised under the blow is a function of force and velocity values and computed by the system automatically using *PDA* software. The *PDA* has an in-built program, which calculates and generates over 30 pile variables based on pile top force, displacement and velocity. Immediate field results in the form of the capacity of the pile, pile top settlement etc, integrity and stresses developed in the pile, etc are obtained.

Presentation of interim report

Interim reports were presented to the contractor/consultants after completion of field-testing in the format given in *Table* 2 to enable proceeding with further works.

Data processing in office

The data was transferred from PDA to a computer using a floppy disk for further processing. A typical blow that verifies the pile capacity was selected for further *CAPWAP* analysis. This was necessary to verify the field capacity and results, since certain parameters were assumed during field testing.

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 were directly inputed from the *PDA*. Based on the measured velocity data, the program computed force required to induce the imposed velocity. Both measured and computed forces were plotted as a function of time and the iterative analysis was continued till there was good agreement between both the curves. If the agreement was not satisfactory, the soil resistances at the pile point and along the pile were adjusted until a good match was obtained. This gave better estimates of the actual static pile capacity measured during field testing, and also the friction and end bearing components.

The *PDA* and subsequent *CAPWAP* analysis indicated the amount of static capacity that was actually mobilised during any blow delivered to the pile during testing. In order to fully mobilise pile static capacity, a pile set in excess of 3-4 mm per blow was required. Should the pile set be less than 3-4 mm, not all the static pile resistance would be mobilised during any one blow and the subsequent *CAPWAP* and *PDA* analysis would under-predict the true ultimate static capacity of the pile. In other words, the ultimate capacity of the pile would be still higher than that indicated after field testing/ *CAPWAP* analysis. This provided some in-built conservatism to the capacities indicated by the *PDA* and *CAPWAP* system in the event of small set being recorded.

Presentation of final report

The final reports are generally presented within 7 days of completion of testing and include the following details.

- Introduction
- Pile details
- Testing equipment
- PDA field testing and results
- *CAPWAP* analysis

Table 2: Format of interim report

Pile No.	*Drop height, m*	*Capacity, t*	*Total settlement, mm*	*Net settlement, mm*	*Remarks*

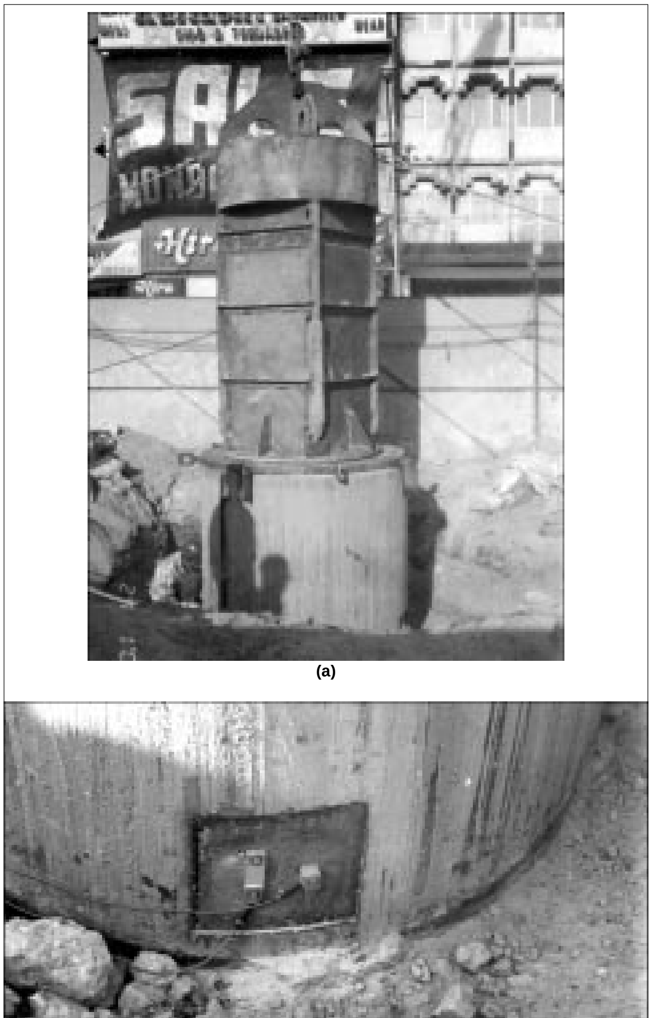
- Discussion of test results
- Conclusions.

Tables 3 and 4 provide the format for complete descriptions of the pile.

A complete *CAPWAP* analysis report was submitted with the final report and included the following in addition to above.

- Total pile capacity in friction and end bearing
- Frictional distribution along sides of the pile
- Changes in pile cross-section if any
- Simulated static test curve
- Force and velocity curve obtained on field.

Thus a comprehensive picture of pile health is obtained using high strain dynamic pile testing.



(a)

(b)

Fig 1 *(a)* 7.5-t hammer used in testing *(b)* Sensors for receiving signals

Table 3: Summary of PDA field test results

No	*Drop height, m*	*Capacity, t*	*Total settlement, mm*	*Net settlement, mm*	*Remarks*

Table 4: Summary of *CAPWAP* analysis results

Pile no	*1*	*2*	*3*
Pile capacity			
Skin friction			
End bearing			
Net displacement			
Total displacement			
Compressive stress			
Tensile stress			
Pile integrity			

High strain dynamic tests

Since static testing is a time-consuming and costly exercise, the adoption of high strain dynamic testing was considered for DMRC project. Tests of these types were not previously conducted on DMRC project sites. It was therefore decided to test a total 12 piles for dynamic testing. Out of these, six piles had been statically tested. The purpose was to establish co-relation between static and high strain tests and to evaluate their reliability. The test method as mentioned in ASTM D4945-89 was followed.

For case histories described below, hammer weights of 7.5 t and 10 t were used and this was equal to 1 to 1.5 percent of test capacity. Height of fall was gradually increased from 1 m onwards upto a maximum of 3 m. A micrometer-based leveling staff was also used to record the permanent settlement during every impact of the hammer. This was to be compared with the settlements recorded by the *PDA*. A 50-mm thick plywood cushion and 50-mm thick steel plate were placed on the pile top to avoid any damage to the pile

Fig 2 Testing of piles

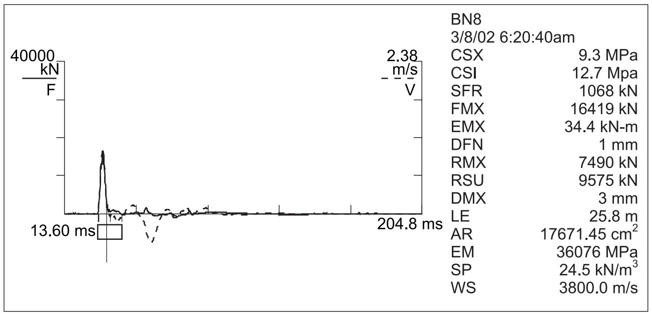


Fig 3 Typical results of PDA

during testing. The testing procedure as per ASTM D4945 was followed. *Fig* 1*(a)* shows that hammer test in progress and *Fig* 1 *(b)* shows the various sensos in position. *Fig* 2 illustrates the testing for piles in progress. *Fig* 3 illustrates a typical force velocity curve and few co-relations for pile foundations.

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 were directly incorporated 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 were plotted as a function of time and the iterative analysis was continued till there was good agreement between both the curves. If the agreement was not satisfactory, the soil resistances at the pile point and along the pile are adjusted until a good match was obtained. This gave 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.

A typical *CAPWAP* analysis output is given in *Table* 5.

Co-relation between static and dynamic tests

Output obtained from high strain dynamic testing was compared with static tests previously conducted on site. Two such typical co-relations are described in *Fig* 4. It is evident that there is a fair match between both the tests. It was also noticed during co-relation studies that one critical parameter on which results of both the tests match is also the time lag between both the tests.

Conclusion

(i) 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.

(ii) It is essential that the person or agency engaged to conduct dynamic pile testing is fully trained in its use to avoid controversies on site.

(iii) The method was significantly faster than an equivalent static load test. The use of concrete blocks or reaction piles/anchors, which is very time consuming and cumbersome, is thus avoided.

(iv) Several piles can be dynamically tested in one day resulting in considerable savings of time, and early completion of the project.

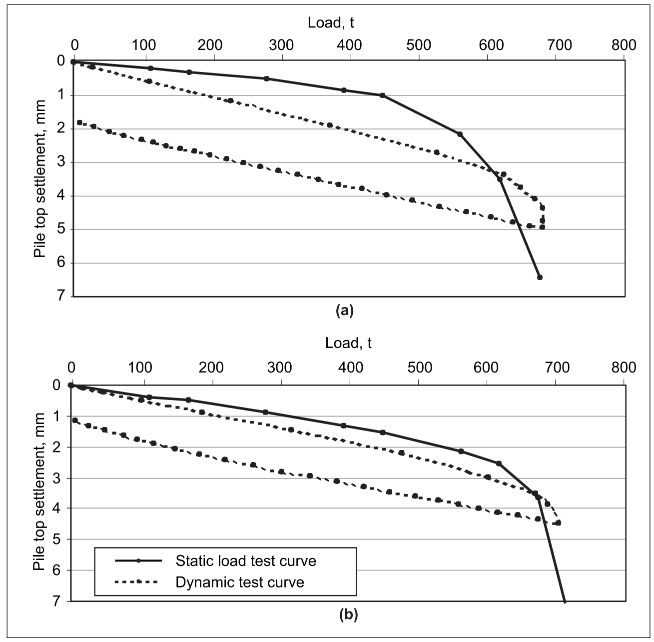


Fig 4 Load versus settlement for *(a)* pile no P359-1 *(b)* pile no P355-03 (Elevated structures on Kohat Enclave to Rithala)

Table 5: CAPWAP final results

Soil segment, nos	*Distance below gages, m*	*Distance below grade, m*	*Ru, kN*	*Force in pile at Ru, kN*	*Sum of Ru, kN*	*Unit with respect to depth, kN /m*	*Resistance with respect to area, kPa*	*Smith damping factor, s/m*	*Quake, mm*
				8949.2					
10	21.7	21.6	599.9	6085.1	2864.1	271.27	57.57	1.213	.898
11	23.7	23.6	1569.2	4515.8	4433.3	760.29	161.35	1.213	.906
12	25.7	25.6	1650.1	2865.7	6083.4	799.45	169.66	1.213	.906
Average skin values			507.0			236.71	52.13	1.213	1.103
Toe			2628.6				1621.8	3.922	1.562

Soil model parameters / extensions	*Skin*	*Toe*
Case damping factor	0.44	0.670
Unloading quake, percentage of loading quake	10	10
Unloading level, percentage of Ru	15	
Soil plug weight, kN		2.0
Soil support dashpot	0.15	1.907
Soil support mass, kN	48.00	48.00

Note: Total CAPWAP capacity: 8949.2 kN (along shaft 6083.4; at toe 2865.7 kN)

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

(vi) 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.

(vii) 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 due to above benefits.

Credit

In India, Geo Dynamics provided the service of high strain dynamic pile testing, with technical support from Pile Dynamics, Inc. Geo Dynamics owns and operates PDA System.

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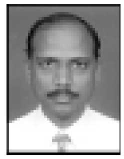
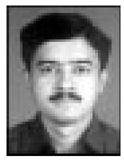
Mr Rajan Kataria obtained his masters degree in structural engineering from The Indian Institute of Technology (IIT) Delhi. He started his career as an assistant manager(designs) in RITES and today has 18 years of experience in structural design. At present, he is the chief engineer/design in DMRC and has played a significant role in the structural design/proof checking of elevated structures for rail corridor of MRTS project.



Mr R. Subramanian has been working with Gammon India Ltd, for the last 18 years and has experience in execution of works and project management on major road, rail bridges, high-rise industrial structures and has also got expertise in handling various complex works on the field of bridge engineering. Presently, he is the project manager of Gammon India Ltd for Delhi Metro Rail Project elevated structure between Trinagar to Rithala.



Mr Ravikiran Vaidya is the managing director of Geo Dynamics, Baroda. He has been endeavouring to make non-destructive testing of pile foundations technology popular in India and getting it implemented on all major infrastructure projects of national importance across the country. He has been involved in getting the government and private sector to adapt, absorb and implement pile dynamic testing and pile integrity testing on projects like NHAI, DMRC and MSRDC etc.

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