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PILE LOAD TESTING IN INDIA - CURRENT PRACTICES AND RECENT DEVELOPMENTS

Sunil S. BASARKAR
General Manager
ITD Cementation India Limited, Mumbai, India
Sunil.basarkar@itdcem.co.in

Sunil S. Basarkar is the Head of Technical services and Quality at the Ground engineering division of his organization. He holds a specialization in Geotechnical engineering, with doctoral research in rock-socketed piles. He has 29 years of academic and field experience.

Ravikiran VAIDYA
Principal Engineer
Geo Dynamics, Vadodara, India
ravikiran@geodynamics.net

Ravikiran Vaidya has popularized various methods of Non Destructive Testing like high strain dynamic testing, integrity, sonic logging etc. in the country. He has 18 years of experience in this field and has worked extensively in India and Middle East. He holds a Masters in Structural Engg. from M.S. University of Baroda.

Summary

Pile load tests are essential to confirm and validate the choice of safe design load and serve as a valuable tool in quality assurance during execution of working piles. Current practice in India still places reliance on conventional tests using kentledge and reaction anchors, considering their ease to test for loads upto 1500MT. There is a growing trend of adopting higher pile loads and this development has given a fillip to advances in testing methodologies and electronic monitoring for assessment of both, external and internal pile performances. Fast track projects, higher test loads and site conditions have given way to alternative methods like Dynamic pile load tests which are now common and Bi-directional loading methods, which since recent years is gaining wide acceptance. This paper presents applications of load tests in conveying vital pile behaviour, their critical assessment and the way ahead vis-à-vis Indian scenario.

Keywords: Pile load test; Dynamic load test; Bi-directional load test; Working piles; Safe load;Maximum test load; Instrumentation; Load transfer; Maintained load; Cyclic load.

1. Introduction

The performance and behaviour of pile foundations resting in a variety of geomaterial is well established. In spite of this fact, the behaviour of these foundations is dependent on local geology, construction methodology and workmanship. These factors make it mandatory to establish pile behaviour under field specific conditions through load tests. Pile load tests, apart from fulfilling traditional roles of design validation and routine quality control tool, nowadays is increasingly utilized as a tool for optimization and continuous improvisation of foundation design and construction practices. Current Indian practice places heavy reliance on traditional load test practices using kentledge or reaction piles. With increase in pile loads, advanced load testing systems have gained entry in India. Dynamic pile load tests as per ASTM D4945 [1] are well accepted after establishment of its correlation with static load test at the site, while

Bi-directional testing, with rise of the testing loads, is slowly establishing its foothold in India. Attention has also increased on pile instrumentation to evaluate frictional resistances and to assess load transfer characteristics.

This paper reviews current pile load testing methods, recent advances and their benefits in delivering economic testing solutions and giving valuable parameters hitherto not common in India.

2. Load Test Classifications, Objectives and Strategies

Testing of piles by direct top static loading still remains one of the most accepted assessments of the pile load-displacement behaviour. Such tests are used to confirm the outcome of the fundamental pile design; and also form a part of quality assurance process on the working piles.

Preliminary pile design is first carried out on the basis of site investigations, laboratory soil testing, and office study. ***Initial pile load tests*** are then carried out to refine and finalise the design load. In Initial load tests, performance of piles under ultimate conditions is intended. These piles are generally tested 2 to 3 times the estimated safe design capacity. ***Routine pile load tests*** are carried out on randomly selected working piles to confirm their intended performance. In these situations, the piles are generally tested to 1.5 times the design capacity. Such tests also serve as valuable quality assurance tool.

Mode of load applications varies in pile load tests. In ***Maintained load method,*** application of load increment and displacement measurement at each stage is carried out till its rate is observed to reach a limiting value of around 0.2 mm/hr. ***Cyclic load application is*** used mostly during initial test to separate frictional and end bearing resistances of a single pile of uniform diameter.

For most projects the main purpose of pile testing is to confirm the design choice of safe load before execution and, in addition, check for compliances to the contract specifications during construction. A broad categorization of objectives may be: (i) design validation, (ii) quality control, (iii) design development and, (iv) research. Basic objectives of load tests are well conveyed by FHWA-NHI [2]:

(i) To obtain detailed information on load transfer in side and base resistance (or lateral soil resistance for a lateral load test) to allow for an improved design (Load transfer test), or

(ii) To prove that the test shaft, as constructed, is capable of sustaining a load of a given magnitude and thus verifying the strength and/or serviceability of the design (Proof test).

In fact, the testing strategy for any load test programme should be aimed to optimise the pile design in terms of its geometric dimensions and marginalise the factor of safety to the best extent. Federation of Piling Specialists [3] identifies risk levels as High, Medium and Low depending on complexity of ground conditions and availability of performance history of piles. According to this risk level, guidelines for deciding the frequency of Initial and Routine load tests are fixed.

Any interpretations of static load tests results require a thorough understanding of the load transfer behaviour of the piles. In this context, papers by Coyle and Reese [4] and Vijayvergiya [5] discuss intrinsic mechanism of load-movements resulting in mobilization of pile side shear and base resistances.

3. Conventional Reaction Sustaining Systems and Applications in India

For vertical load tests, load application in conventional practice is by top down technique through a set of hydraulic jacks. Ground conditions and test load magnitude will generally govern the reaction sustaining methods and are discussed in following sections. Applications for pull out are also stated.

3.1 Top down load applications

Common reaction sustaining technique is by **Kentledge method,** where reaction arrangement exists in form of concrete blocks or any counter weights that rests on set of secondary girders, which in turn are supported by primary girder. The primary girder is sandwiched between the hydraulic jack and the secondary girders. The counterweights have to be sufficiently higher than the test load to prevent cantilever action of the secondary girders during loading. As an illustration, reaction by Kentledge load of 18.75MN for a high rise residential tower at Kolkata can be seen in Fig.1. This arrangement was made for Initial load test on a pile to validate its 9.00 MN design capacity by adopting a low load factor.753 concrete cubes of 1 m^3 size each were used with a loaded area admeasuring 12 m x 11 m. Test pile was 1000 mm diameter and 58 m length, passing through silty clay/clayey silt for top 51 m (SPT N varying from 15 to 75), with lower 7 m resting on dense sand with N>100.

Fig.1: Load test using kentledge arrangement

Fig. 2: Load test using anchor piles

Reaction Piles or Active Anchors are more convenient where rock and competent stratum are available at a shallow depth. Such arrangement consists of two or more reaction piles or active anchors located on either side of a test pile. In order to minimise the interference between test and anchor piles, a minimum distance of three times the pile diameter is maintained between these piles.

A reaction beam is placed on top of the anchor piles and the test pile is loaded by utilising a hydraulic jack placed co-axially on top. This results in applying compressive load on the test pile and uplift load on the anchor piles. Since the equipment and girder requirements are small, foot print area is relatively small; for instance, a test load of 8.00MN with reaction arrangement comprising four active anchors of 2.20 MN capacity would require and area of approximately 6 m x 2.2 m area.

In one of the sites at Karwar located on west coast of India, a vertical load test was conducted. Steel piles were driven on reclaimed area through a larger diameter MS Liner upto weathered rock level, so that contribution only from socketed rock was available to the pile. This arrangement modelled the behaviour of marine piles, designed for resistance arising solely from weathered rock. Safe design load on this driven steel pile 850 mm outer diameter and with a conical bottom shoe was 3.50 MN. A 9.00MN reaction arrangement was made comprising eight rock anchors, four on each side (Fig. 2), each of 1.16 MN safe capacity, deriving strength from 9 m fixed length in rock.

A similar arrangement was also made at Tuna port near Kandla, Gujarat. A test pile 1500 mm diameter and 35.50 m depth, when loaded to 21.103 MN indicated displacement of 8.98 mm with observed rebound of 7.50 mm. Sixteen active anchors each of capacity 1.32 MN, with arrangement for housing four anchors at each corner, each with 10 m fixed length in amygdaloidal basalt were installed. The test pile, after 22 m of clayey silt/ silty clay layers, passed through 10m of highly weathered amygdaloidal basalt (average UCS of 25 MPa), and then socketed about 3.5 m in moderately weathered amygdaloidal basalt (core recovery excess of 97% and RQD in a range of 25 – 50%) with UCS of 100.0MPa.

In another instance, at Noida, near Delhi, piled raft supported on bored cast-in-situ pile of 1200mm diameter was proposed for a high rise commercial tower. Load test program was planned to determine and maximize the safe pile capacity to achieve most economic pile-raft combination. The ground conditions were daunting, since the site was situated at close proximity of Yamuna river and comprised loose to medium dense sand to about 5 m (SPT N values between 4 to 34) followed by a medium dense to dense sand (N values 10 - 93) upto an investigated depth of 40 m. Pile bore stability was the critical factor identified and a combination of stability fluids were suggested for arriving at an economic and reliable piling proposal. Five test piles were planned, of which three load tests of relevance to this paper are summarized in Table 1.

Table 1: Noida load test details

Test Pile no.	Pile diameter (mm)	Pile length (m)	Bore hole stability fluid	Computed design load (MN)	Applied maximum test load (MN)	Pile top dis-placement (mm)
TP1	1200	40.00	Bentonite	5.40	7.82	131.58
TP3	1200	34.00	Polymer+ Bentonite	5.40	17.00	127.642
TP4	1200	34.00	Polymer	5.40	17.00	21.40

A reaction arrangement for all these load tests comprised a 22.00 MN capacity kentledge, with maintained loading method as per provision of IS: 2911 (Part 4) [6]. Comparative load-displacement curves for these tests are reported in Fig. 3, and the safe loads revealed for TP1, TP3 and TP4 were 3.13, 6.17 and 9.80MN respectively.

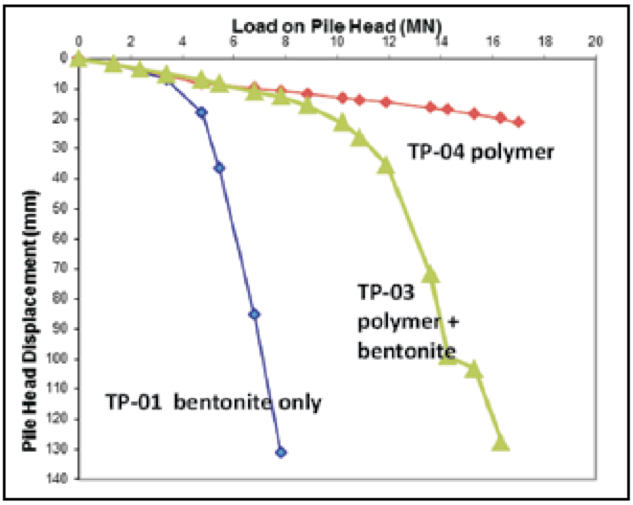

Fig. 3: Borehole stability fluid performance - comparative load-displacement curves

As seen from the comparative curves, test pile TP03 with engineered polymer fluid was able to deliver a very high pile capacity. With increase in pile capacity, a significant reduction in the raft size and hence overall foundation cost became evident.

At this point it is important to note that despite best engineering attention in field, for large diameter piles stabilized with bentonite slurries, complete cleaning of pile bores is still a matter concern. Under such situation, ability of polymer fluids, which according to the manufacturer's product literatures may improve frictional resistance at pile-soil interface, and becomes an important factor contributing to increase in pile capacity.

The conclusions on use of polymer fluid are based on site specific performance and should be used with caution at this time. Before generalization, dedicated laboratory and field studies in various soil conditions are desired to conclusively prove a positive contribution of polymer based slurry in improving the frictional contributions.

3.2 *Pull out load tests*

Pull out load tests are carried out by connecting the test pile reinforcement to a primary girder, which is upward loaded with hydraulic jacks. A single hydraulic jack of high capacity may be co-axially placed above the test pile; or alternatively, jacks are placed atop reaction piles.

At a project site at Kalma, located near Raigad town at Central India, a pull out load test (Fig. 4) was conducted to confirm performance of a 900 mm diameter RCC bored raker pile with a safe uplift load of 2.02 MN. The pile passed through 4.50 m of sandy clay, and 2.50 m of soft rock, before being socketed 6m into hard basaltic rock. Summary information of this load test is reported in Table 2.

Fig. 4: Pull-out arrangement on a working pile at Kalma

A 5.00 MN capacity hydraulic jack was used, and pull-out load was applied by lifting the main rebars of the pile through the jack load, and transferring the load to the primary girder by 22 nos. of 32 mm diameter MS bolts (Fig. 4). Average rock-pile bond mobilized under test Load was 0.1265 MPa, which was very low indicating very high reserve strength in Pile.

Table 2: Pull-out load test information – Kalma case study

Pile No.	Pile dia. (mm)	Pile depth (m)	Pile type	Safe pull out load (MN)	Test load (MN)
P05	900	12.96	Bored cast-in-situ working raker pile (1H:10V)	2.02	3.03 (applied co-axially)

4. Measurement of External and Internal Pile Performances

Two main types of movement measurements in a load test are pile head displacement and incremental strain measurements internally along the pile length.

4.1 Pile head displacement measurements

Pile head displacements are required in all pile load tests and are measured with dial gauges or Linear Variable Displacement Transducers (LVDTs). Dial gauges are used in areas where the test pit requirements are shallow and easily accessible. In the areas requiring deep test pits where, due to safety reasons when access is restricted during loading, LVDTs are often deployed, with their read-out unit at safe and convenient location. A surveyor's level may also be used for measuring the axial pile movement; more preferred as a matter of cross check rather than as a primary means of movement measurement.

4.2 Common instrumentations for incremental strain measurements

Incremental strain measurements are used to determine the distribution of load transfer from the pile to the soil and are generally considered as an optional measurement feature, but are finding increasing use in India.

Electronic strain sensors of various forms are available which can be mounted along the pile length at various locations before the pile is installed. In piles, these sensors can be welded to the reinforcing bars and wires can be brought near from the top through a PVC casing. Strain sensor output are read electronically using portable readout boxes or with dataloggers.

Telltales or Strain rods also form one of the vital instruments and normally consist of PVC tubing extended to steel end plates embedded inside a concrete pile or welded on the steel pipe at various locations along the pile length. Normally, telltale readings are referenced to the top of the pile. By noting the location of the specific telltale rod anchor plate and by measuring the relative movement of the individual rod, elastic shortening of pile at that location can be obtained.

4.3 Instrumentation case study

Pile instrumentation is adopted particularly to understand the load transfer characteristics or when history of pile performance at the project site is not available. For a particular project site at Noida, instrumented pile load test was performed on one of the test pile TP02 of 1000 mm diameter and 35m depth below the cut-off-level. Instrumentation comprised four levels of vibrating wire strain sensors (Fig. 5), four at each level as indicated. The test pile was step loaded to 15.11 MN through 13 loading increments (Fig. 6). Strain readings were recorded and converted to appropriate load values with concrete elastic modulus, E_c 25000.00 MPa (for M25 grade pile concrete), using relationship Q=A.Ec.ε where, Q is the pile load at the strain gauge level, A= CS area of the pile & ε= measured strain. Using strain information and interpretations, curves for strain. vs. pile top load (Fig. 7), load distribution curves (Fig. 8) were plotted. Information furnished by the instrumentation is compiled in Table 3.

Table 3: Unit load contributions in Test pile TP02 under 12.09 MN maximum pile top load

Pile depth range (m)	Load transferred (MN)	Unit shear mobilized (KPa)	Remarks
0.00 – 13.10	2.174	52.80	
13.10 – 23.10	3.723	118.50	
23.10 – 32.10	4.755	168.18	
32.10 – 35.00	1.436	-	Includes shear and base contribution

Instrument observations indicated that strain gauge readings at -3.1 m could not be relied, probably due to lateral spread of the applied load along the pile cross section. Again, strain gauge readings beyond application of 12.09 MN load could not result in

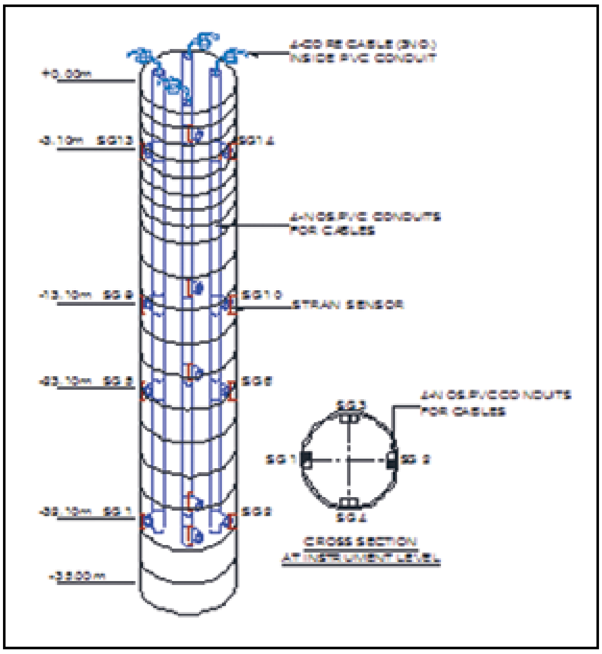

Fig. 5: Scheme for pile instrumentation

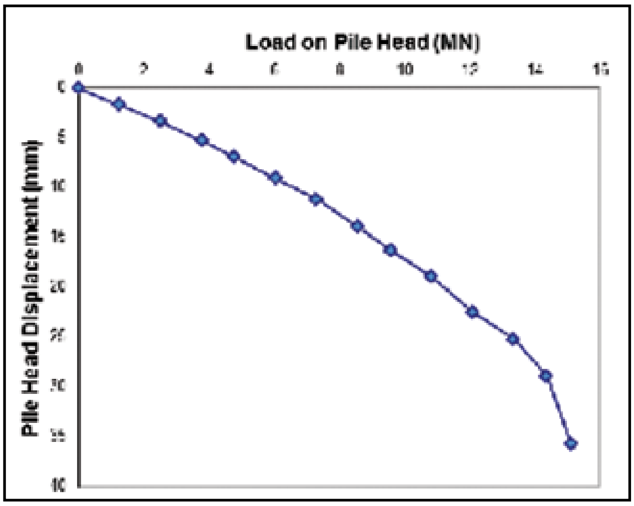

Fig. 6: Pile top load-displacement curve

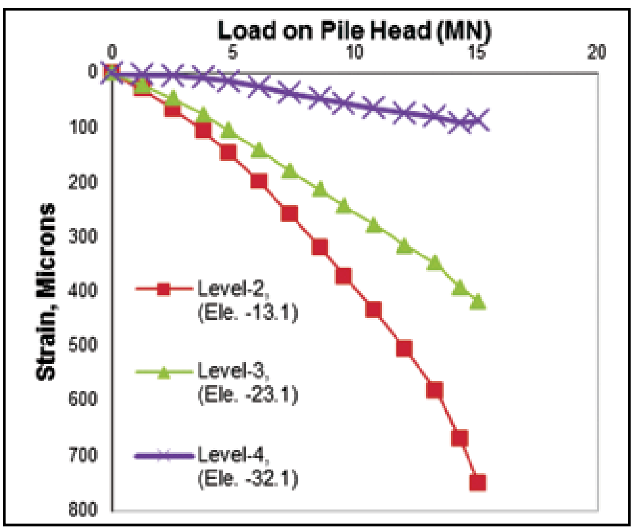

Fig. 7: Strain .vs. pile top load curve

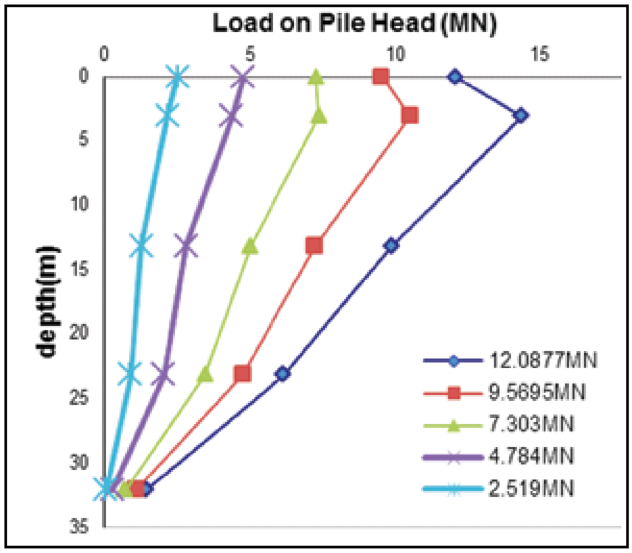

Fig. 8: Pile load distribution along depth

logical load interpretations, and hence were overlooked. With these exceptions, the instrumentations had been able to convey the unit shear contributions and had affirmatively confirmed predominant frictional pile with 88.12% of the load resisted through friction in top 32.1 m length of the shaft.

5. Dynamic Pile Load Test – Advent and Practices in India

High Strain Dynamic Load Tests (HSDPT) are the most common method to test the piles after static load tests. The method has now been routinely accepted across sectors like highways, railways, power, marine, oil & gas and real estate projects. The most common practice is to conduct some reliability studies by loading the same pile statically and dynamically and compare the findings before allowing high strain dynamic tests at the project site. Based on the criticality, number of piles and the stretch of each project, one or more reliability study is conducted at each project site to verify the HSDPT output. Correlations or reliability studies provides checks on the reliability of HSDPT in unknown stratum before allowing its use. Since the method requires documented expertise and high integrity of the personnel conducting the test, such studies also help confirm the expertise of the personnel or the agency conducting the tests.

The test is conducted as per ASTM D4945 [1]. For bored piles, the method involves impact of a hammer of 1-3% of the test load and 7-10% of the self-weight of the pile, whichever is heavier. Sensor readings for strains and accelerations are measured and converted to forces and velocities in the pile. The field capacity is obtained by a series of impacts and the test is stopped. The data obtained is then modelled using proprietary software CAPWAP™. This software discretizes the pile into a series of elements and helps in obtaining the soil resistances along the length and by end bearing. The software generates a Match Quality (MQ) number which indicates the quality of analysis. MQ of less than 3 or in some cases upto 5 are most preferred for acceptance of the test results. A recent technical paper by Vaidya, *et al.* [10] documents in detail the parameters to be monitored before acceptance of the test results. It should also be mentioned that the high strain dynamic test method correlates well the Davisson's criterion of failure which is more conservative compared to the values derived from the current Indian code of piling practice [6].

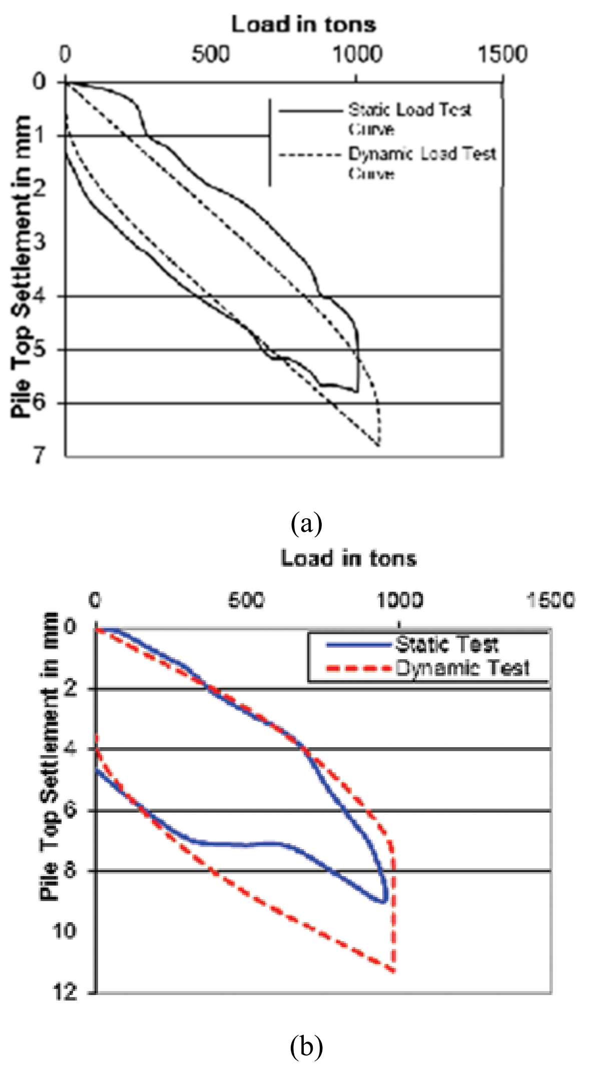

Fig. 9: Reliability studies on dynamic load test. (a) Mumbai case study (b) Delhi case study

A database of more than 150 such case studies in a variety of soils is now available across India and some of it is also available as published literature (Basarkar *et al.* [11], and Mhaiskar *et al.* [12]). With availability of large database is available, the authors have used the method for initial load tests at several project sites to obtain the ultimate load which is difficult to obtain with static load tests if design is conservative. Two reliability studies in rock and in soil are mentioned.

Fig. 9 (a) shows a reliability study for a major infrastructure project in Mumbai. The pile was 1m in diameter and with a short depth of 9.4 m installed into rock for bottom 2 m. Fig. 9 (b) shows a reliability study for a project in Delhi for 1m diameter pile with depth of 27 m installed into a stratum that had fill for 2 m, followed by dense to very dense brown silty sand from 2 m to 12 m and further from 12 m to 30 m.

5.1 Pullout tests using HSDPT

Several published literatures including those of authors have reported good match between computed and measured values of soil resistances along pile length and end bearing when ultimate pile capacity is reached. The friction obtained from the static or dynamic load tests is basically related to the uplift capacity of the pile. After allowing for some ambiguity in modelling of friction in HSDPT, typically 80% of the friction obtained from the HSDPT test is considered as the uplift capacity of the pile [17]. The second author has used this approach at several projects successfully and a database is also available for driven piles.

6. Bi-directional Pile Load Tests in India

Bi-directional technology employs Osterberg type Load Cell (O-cell). An O-cell is a sacrificial jack like device attached to the pile rebar cage [7]. Hydraulic lines and telltales extend from the O-cell to the top of the pile to monitor the movement of the pile base as the O-cell load is applied (Fig. 10). Since the O-cell after being loaded, derives reaction from the pile-soil and pile-base resistances, it is important that the location of placing of O-cell is correctly identified and the pile does not have any construction deficiencies particularly at the bottom.

Developments and advantages of Bi-directional tests in India using O-cell are well brought about by Ayithi *et al.* [9]. According to Ayithi *et al.* [9], first O-cell tests were

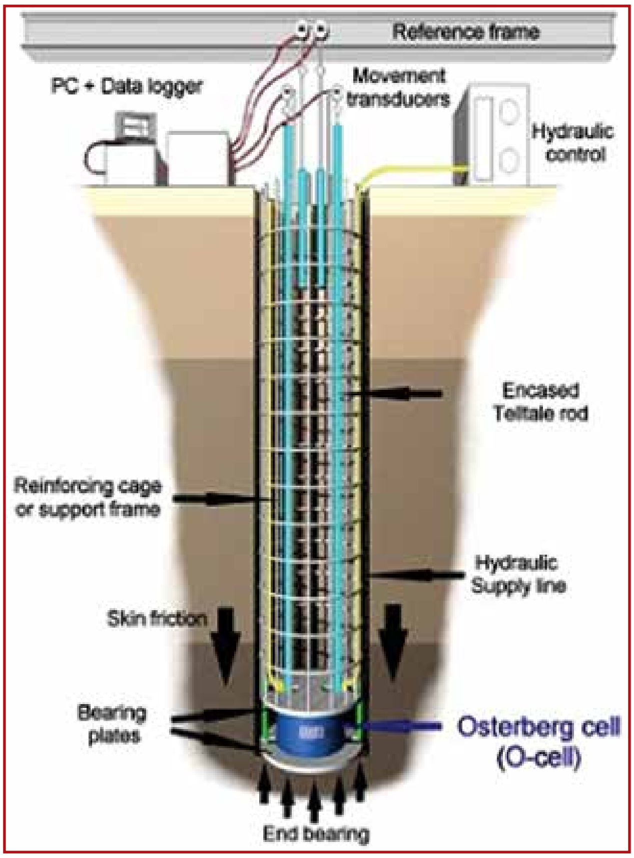

Fig. 10: Schematic of O-cell based pile testing [8]

conducted in India during 2001 for Bandra-Worli sea link project at Mumbai. Till date, about 15 O-cell tests have been performed in India and include four load tests at iconic World Crest Towers and Infra Wadala (2 nos), both at Mumbai. One case study is briefly outlined conveying the application to high capacity sockets for optimization.

6.1 World Crest Tower, Mumbai case history[9]

At World Crest Towers, two tests were performed on dedicated piles with information summary reported in Table 4.

Table 4:Pre-design O-cell test on pile

Test pile no.	Designation	Diameter (mm)	Length (m)
2873-1	Test pile	1200	26.70
2873-2	Test pile	1200	26.70

The test piles after 3m fill layers were taken into weathered to slightly weathered Tuff layer. This single O-cell assembly system located 4m above the pile tip, had instrumentation consisting of paired compression telltales and pile toe telltales to facilitate measurement of pile compression above and below O-cell. Paired strain sensors, four above and three below the O-cell were installed to study load transfer. A maximum bi-directional load of 38.00 MN was applied through O-cell.

For a socket rock comprising weathered Tuff, design value of side shear resistance was 0.1 MPa. The O-cell strain gauge data revealed a very high side shear resistance of 1 to 2 MPa. This load test output lead to reduction of the length of the working piles to 19m, thus contributing to a significant savings in foundation costs. All structural loads were taken entirely by side shear resistance of socketed piles. O-cell test carried out on two optimised working piles 2894-1 & 2894-2 (Table 5) indicated similar capacity as the test piles.

Table 5:Worli Crest Tower case study:O-cell test results

Test pile no.	Maximum load applied (MN)	O-cell expansion (mm)	Max. side shear mobilized (MPa)	Max. end bearing mobilized (MPa)
2873-1	38	3.97	1.55	None transferred to toe
2873-2	38	14.10	2.00	
2894-1	34	3.58	1.66	
2894-2	31	3.21	1.00	

The above case study illustrates a safe and reliable application of O-cell for high capacity load application hitherto considered very tedious for conventional load tests. Through O-cell load application, complete mobilization of both side shear and end bearing are possible which can yield valuable insight on their resistances and lead to a highly economic pile design.

7. Critical Appraisal of Pile Load Test Practices in India

In India safe vertical compression pile loads commonly vary from 0.60 MN to 15.00 MN, while uplift and lateral loads vary in the range of 0.20MN – 3.50 MN and 0.02 to 0.15 MN respectively. Kentledge loads beyond 20.00 MN requires large sized loading platform and invites objectionable safety concerns in

India, though, there are reported instances of applying kentledge method for test load upto 27.50 MN. Under special cases abroad, reaction system using multiple reaction girders and anchor piles have been used to test upto 40.00 MN, with probably highest load of 57.00 MN performed in Taiwan [2].

Maintained load test is common and frequent practice to verify the safe loads, while cyclic load tests are generally preferred for an approximate assessment of side shear and end bearing contributions of a pile. Indian practice of this test is probably an offshoot of Slow maintained load method referred to as the standard loading procedure in the ASTM D-1143-81 [13]. Loading cycles are generally 20% of the computed ultimate load.

Limitations of cyclic load interpretations are well eliminated by use of strain sensors along the pile. With the hardware and installation costs coming down, use of instrumentations is on upswing in India, though not at all at par with their use and reliance abroad. Among the strain sensors, the vibrating wire type is very common. The current practice is to install 2 or 4 strain sensors at the top, near the middle and then near the tip of the pile. This leads to a high degree of approximation. More sensors need to be placed and typically the distance should not be more than 3 to 5 m to facilitate better understanding of load transfer behaviour. In future, increasing use of instrumentation aided with better interpretation is expected to lead to optimization of pile design and installations.

Bi-directional load tests have been used sparingly where project costs permits or when computing rock end bearing is essential. For initial tests where test loads higher than 30 MN are anticipated, Bi-directional tests can be preferred if the project cost permits.

HSDPT offer speed, economy and reliability when site arrangements are proper and tests are done by expert personnel with good integrity. The method now is a part of contract documents of various government bodies and is well accepted in the real estate sector. Load tests from 0.1 MN to 20 MN are commonly done across India. Typically 0.5-2% of the working piles are tested with HSDPT and at several projects now where past reference or database is available, the method also has been used for initial load tests. Since the method requires expertise, it is important that the end client knows basic monitoring during the test program, otherwise abuse of the tests in some instances have also been reported.

Performance of large and small diameter piles as a separate entity needs to be appreciated. The Indian code does differentiates them by adopting an interface value of 600 mm and allocating separate displacement criteria of 12 mm and 18 mm respectively for small and large diameter piles to arrive at a safe load. Load test experiences on piles indicate that a better interface for large and small diameter piles would be 900 mm with displacement criteria for inference of safe loads as 15 and 20 mm respectively.

Literatures on safe pile load criteria are abundant, but probably the best compilation with critical reviews is done by Fellenius [14]. The criterion proposed by Davisson [15] is more common in United States and several countries and also used for correlation with dynamic load tests. Chin [16] has proposed an extrapolation method to obtain approximate value of ultimate load although with high degree of variability.

Load tests, unfortunately in India, has yet to see their frequent use as a tool for optimization and research, a reason probably attributed to fast track nature of the projects, where a green signal to proceed is accorded solely on the fact that the pile meets the minimum design load requirement, irrespective of the margins.

8. Concluding Remarks and Future Outlook

The foregoing sections presented trends on pile load testing with specific reference to Indian practice. For a normal range of vertical compression pile loads, conventional test methods are commonly used, while high strain dynamic tests are increasingly used for routine piles.

Future trend is to adopt large diameter piles, monopiles and rock socketed piles which will introduce a fresh demand for high capacity load tests. Considering the safety restrictions and reaction load feasibility, there is a scope for Bi-directional load tests with multiple use of O-cell which has a potential of applying loads even upto 300.00 MN. While, this load test has already gained acceptance in Indian conditions, albeit at higher cost, other technologies like Rapid load tests have not yet been performed in India due to various reasons that includes costs, permissions and database.In the current decade, embedded data collectors are finding applications in US and Europe particularly for driven piles. However, published literatures on their performances and experiences are scarce and therefore, more applied research is desired validating their performance for gaining global confidence and acceptance.

Instrumented Pile Load tests with vibrating or sister bar strain sensors and tell tale extensometers as a tool for optimizing pile design will still take time, as with limited sensors only limited data is available, and there is hardly any discussion or emphasis on good interpretation. It is a known fact that if a combination of some of the methods mentioned in this paper is used at project sites, then the cost of such testing can be offset by the optimization that can be obtained with the results of these load tests. In addition, sizeable reduction in foundation costs is possible.

The ability of pile load testing as a value engineering and geotechnical and structural optimization tool is yet to see light of the day in India. This practice would not only benefit in financial terms but has significant importance in sustainability.

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