CAPWAP Complexities and Case Studies for Pile Foundation Testing in India

Ravikiran Vaidya[1], and Sujan Kulkarni[2],

[1]Principal Engineer, Geo Dynamics, 49, Atmajyoti Nagar Society, Ellora Park, Vadodara, India; e-mail: ravikiran@geodynamics.net
[2]Senior Manager (Technical), Geo Dynamics, 49, Atmajyoti Nagar Society, Ellora Park, Vadodara, India; e-mail: sujan@geodynamics.net

ABSTRACT

Bored pile foundations typically range from 300mm to 2m diameter and are installed in a variety of soils. Since they are under-ground and are installed with various techniques, methods and with fast track construction being a norm, QA/QC becomes a vital requirement for bored piles before acceptance. In addition to conventional static load tests which yield little information on failures, High Strain Dynamic Pile Testing (HSDPT), Low Strain Integrity Testing (LSIT), Cross Hole Sonic Logging (CSL), Parallel Seismic Method provide substantial information on quality and capacity of bored piles. The methods have also been extensively used for forensic engineering purposes to investigate the quality, reasons for failure, and also when no prior information is available about the depth or capacity of pile foundations.

Case Pile Wave Analysis Program (CAPWAP®) analysis is an integral part of High Strain Dynamic testing for bored piles. However, there is not much awareness of the complexity of the CAPWAP analysis in India, and generally, it is assumed that the initial findings as seen on field are close to the final result for the pile. CAPWAP and high strain testing require knowledge of geotechnical and structural behavior pile, soil and importantly also knowledge of wave mechanics.

This paper briefly describes the fundamental features of CAPWAP and complexities associated with it. The paper includes several case studies where HSDPT, CAPWAP and PIT were used not only for QA/QC, but also as forensic tools for pile foundations to identify failures causes. One case wherein pile foundations that were thought to be suspect were actually proven to be of good quality because of forensic engineering is also described.

INTRODUCTION

HSDPT with the Pile Driving Analyzer® (PDA) was first offered by Pile Dynamics in 1972 following a decade of pioneering research at Case Western Reserve University. Later low strain integrity testing using Pile Integrity Tester, Cross Hole Sonic Logging, and Thermal Integrity Profiling was also popularized by PDI worldwide. Today, these methods are used across six continents and in more than 90 countries.

The original research on dynamic pile testing began at Case Western Reserve University more than 55 years ago (Eiber, 1958). The Ohio Department of Transportation (ODOT) and Federal Highway Administration (FHWA) subsequently funded a project starting in 1964 for further development of the technology (FHWA Ref. Manual – Vol. 2, 2006). A detailed historical development of these technologies has been documented by Hussein (2004).

High Strain Dynamic Pile Testing along with CAPWAP was introduced to India in the later part of eighties and subsequently the first author (Vaidya, 2001, 2004) for the first time in 1998 successfully demonstrated its reliability and use for major infrastructure and real estate projects. The entire process of dynamic testing involves three phases. The first step is selection of hammer for bored piles. The second step is actual field-testing which also requires an experienced engineer to monitor the tests. If the data collection is poor and yet an output is generated then the final results have no relevance. The significance of data collection and data interpretation is adequately described by the first author and various papers as per mentioned references. The third step is post processing of data by CAPWAP analysis. For bored piles, it is mandatory that the data is further analyzed by CAPWAP to evaluate correct damping, pile profile, friction distribution etc. and only then can the correct capacity and load settlement curve is possible.

The HSDPT and CAPWAP requires expertise and practice which can generally be only obtained with dedicated analysis, sound understanding of the subject and importantly sound integrity of the engineer doing the analysis. Any intentional or unintentional error can lead to an incorrect end result, which in some cases can be significant; in many cases, data distortion or manipulation leads to loss of trust in a well developed technology. Although lots of literature is available on HSDPT, there is limited information about CAPWAP particularly in the Indian context. Hence, an effort is being made in subsequent section to elaborate the CAPWAP analysis and complexities associated with it as this has a large implication when these methods are used for forensic engineering purposes.

CAPWAP ANALYSIS AND COMPLEXITIES

CAPWAP (CAse Pile Wave Analysis Program) is signal matching procedure in which force and velocity data collected during HSDPT is imported in CAPWAP software, iterative analysis is performed to derive pile capacity, and pile profile viz. bulges, defects etc. It is standard program worldwide for the prediction of simulated static load test curve from HSDPT data. The analysis consists of adjustment of various soil parameters until measured and calculated pile top variables such as force and velocity reach a reasonable match. In other words, the method computes static and dynamic soil resistance parameters for pile along the depth and at the toe. The analysis is continued until a best possible match between computed pile top variable such as force or velocity and its measured equivalent is obtained. This can only be obtained by changing soil resistances along the pile depth based on the wave profile. Such an analysis of changing soil parameters and resistances can only be done by an engineer familiar with the pile behavior under impact. The CAPWAP is based on the wave equation model, which analyses the pile as a series of elastic segments and the soil as a series of elasto-plastic elements with damping characteristics, where the stiffness represents the static soil resistance and the damping represents the dynamic soil resistance. CAPWAP separates static and damping soil characteristics and allows for an estimation of the skin friction distribution and the end bearing component of pile. Following sections elaborate the CAPWAP in detail along with complexities associated with it.

CAPWAP performs actual calculations by dividing the pile into series of segments which are individually of uniform properties. The pile is divided into N_p segments of uniform cross section with normally ΔL = 1m length (which can be changed by user if required) such that the wave travel time of all segments is equal. The soil resistance is also divided into N_s shaft resistance forces. Refer to Figure 1 for schematic of CAPWAP model.

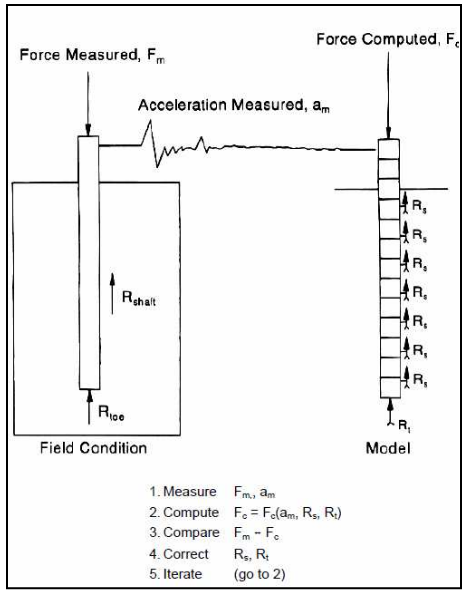


Figure 1 Schematic of CAPWAP model

The CAPWAP modeling consist of following elements: Pile profile, Slacks, Pile and soil Damping, Impedance, Toe Gap, Plugs, Radiation damping etc. These parameters are briefly explained below. Because of so much inputs and variables the analysis becomes quite complex and results in non-unique solution. However, if two individual experts perform the analysis then often it is seen that their solutions are very close and similar if not identical.

The first basic step before starting the CAPWAP program is to select a correct blow for analysis that depicts the pile behavior wherein either the pile has reached the required test load during field testing or has shown a permanent set of 4mm per blow or more possibly implying ultimate pile capacity. Once the selected blow is imported into the program the CAPWAP generated a computed force or wave-up curve based on the measured velocity curve. The program should typically be continued by adjusting the damping parameters so as to ensure that the measured and computed forces and velocity curves match reasonably. The Case skin damping is specified by Js and the Case toe damping is defined as Jt. These are related to the Smith soil damping parameters Ss and St and are provided as the original model was based on the Smith damping parameters. The analyst may also choose shaft and toe damping type options and they can be linearly viscous, smith or combination of both.

Note that an increase in damping during analysis results in a reduced capacity estimate and vice versa. There is a guideline for damping parameters and they depend more on the grain size. However, since actual pile behavior is complex and is tested generally for proof loads only, these parameters should carefully be selected based on engineering judgment and geotechnical behavior during field pile testing. The quakes also need to be computed and this requires trial and error inputs of skin quake Qs and toe quake Qt. The skin quake does not to vary too much and generally ranges from 1mm to 4mm. However, the toe quake may range from 1mm to 50mm based on pile movement and soil type.

Once the damping and quakes are modeled, it is sometimes recommended to look at confining soil resistance on the pile which can be adjusted with the radiation damping option Sk inside the software. Broadly if the pile is uniform and with no major defects, bulges or cracks, the above parameters maybe produce a good output which the CAPWAP defines in terms of Match Quality. Typically, Match quality is a number generally atleast less than 3 or 5 (Vaidya, GL, 2013). However, bored piles are rarely like pre-cast or steel piles with uniform profile and uniform material properties. In several cases, the piles may have bulges or hard layers of soil, defects or hairline cracks. The quality of the pile head may also require extensive proper modeling.

Once the soil modeling is complete, based on the understanding of wave mechanics and wave profiles, it may be required to model the pile profile by changing the pile area or elastic modulus, also called pile impedance. These parameters are useful not only in obtaining the pile profile but they also affect the unit resistance calculations. It is recommended that before changing the pile profile, information like concrete pour card, bore log data, tremie choke, delay in concrete, etc. should be reviewed. This will help better model bulges and also provide information not only about defect but the magnitude of defect inside the pile. The pile model may include tension or compression slacks to model splices or cracks. Modelling cracks or splices with slacks is not a simple task because two models exists and each model involves two unknowns. The appropriate slack model and its location has to be found by trial and error input of slack values at various elements. A typical input screen is shown below as Figure 2 and Figure 3 highlights the primary input parameters of the CAPWAP analysis.

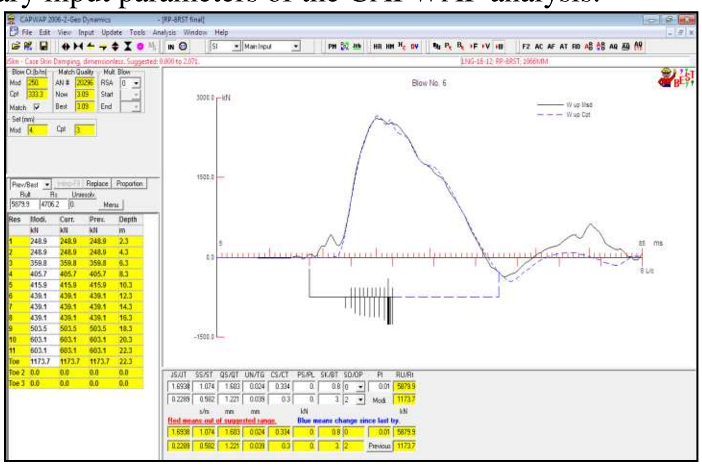
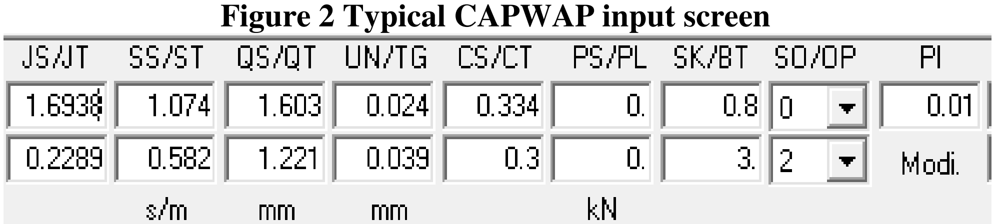


Figure 2 Typical CAPWAP input screen



JS/JT – Case skin and Case toe damping parameter; QS/QT – Skin and toe quakes
SS/ST – Smith skin and Smith toe damping parameter; UN – skin friction unloading limit
TG – Toe gap; CS/CT – Skin and toe unloading to loading quake ratio; PS/PL – Soil Plugs
SK/BT – Radiation damping and skin and toe; SO/OP – Skin and toe damping selection;
PI – Pile damping

Figure 3 Primary input parameters

For piles on a very hard end bearing layer, a gap beneath the pile toe sometime exists just before the pile toe starts to move downwards, which is known as toe gap and can be modeled in CAPWAP. Furthermore, the inertia force may be caused by the mass of the soil sticking to the pile trapped underneath or to the sides which is known as soil plug (acceleration dependant resistance) and can be modeled in the analysis if required. Other input parameters include unloading and reloading multipliers, skin and toe unloading quake multipliers etc., which make the analysis more complicated.

Thus, it is evident that CAPWAP analysis comprises of several variables for each segment of the pile that need to be modeled. . It is extremely important to keep these parameters within specified range as provided by the software based on the measured force curve, so that a meaningful and acceptable output is obtained. Each one of these parameters has certain limitations and its application directly affects the match between measured and computed wave and eventually match quality.

The effort of the analyst should be directed towards obtaining an acceptable match quality without compromising on the geotechnical or the structural behavior of the pile and this must reflect in the analysis. The CAPWAP also offers an auto match that may produce a good match quality but is not recommended for bored piles due to the complexities involved. Results with higher match quality may be acceptable with valid justifications. Thus, the CAPWAP analysis if done correctly provides useful information not only on the load settlement curve but also about friction and end bearing, hammer performance, soil behavior, pile integrity, pile stresses etc. A good forensic investigation thus will require a sound knowledge of CAPWAP in addition to field data collection with Pile Driving Analyzer. A few case studies of using the PDA/CAPWAP and other tools to investigate pile foundations are summarized below.

CASE STUDIES FOR PILE FOUNDATION TESTING IN INDIA

A project site in Cochin

For a project site located in Cochin, the subsurface conditions consist of layers of sand and clay. A generalized subsurface condition is presented as Table 1. Bored concrete piles having diameter of 800mm upto 48m length, and 1200mm upto 75m length were installed at the site. The design loads were ranged from 500tons to 1100tons depending upon diameter and depth. There were apprehensions about 75m length of pile with 1200mm as this was the first time such a long pile was installed in India.

PIT was performed on around 500 piles. PIT graph for a 75m long pile is presented in Figure 4. Generally, no major problems were reported with the PIT tests. Although L/D ratio for these long piles was quite high (i.e. around 62), satisfactory data was collected using PIT. Here it is important to note that it is possible to test long piles with PIT even though old literature suggests that testing is possible upto an L/d ratio of 25-30. There is no rule of thumb for L/d ratio and it depends on the soil and pile profile. Soils with high resistance and/or piles with major bulges are difficult to evaluate even for low L/d ratio of 20, whereas uniform piles with low resistance for significant depth can be evaluated even for longer lengths as seen in the current case.

Table 1 Generalized Subsurface Profile – A project site in Cochin

Layer No.	Soil Type	Depth (m)		Layer No.	Soil Type	Depth (m)
1	Fill	0-0.75		7	Medium Stiff Clay	33-41
2	Soft Clay	0.75-11		8	Dense Sand	41-45
3	Soft Sandy Clay	11-20		9	Clayey Sand	45-57
4	Sand	20-28		10	Silty Clay	57-59
5	Very Stiff Clay	28-31		11	Hard Clay	59-62
6	Medium Sand	31-33		12	Clayey Silt	62-68

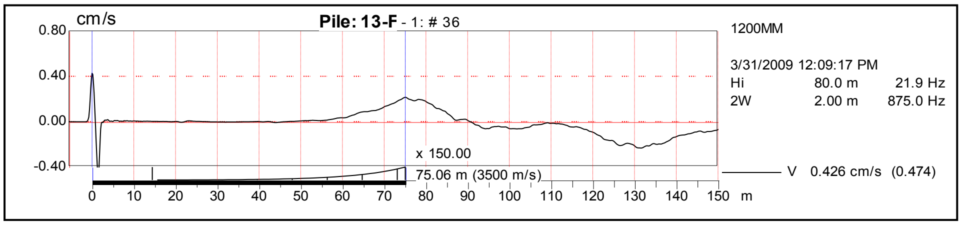


Figure 4 PIT data collected at a site in Cochin

HSDPT was also performed on 15 piles having 1200mm diameter after establishing its reliability with static load test. The reliability study was obtained by testing the same pile statically first and then with HSDPT. The study is presented as Figure 5. Eventually, HSDPT was conducted using 10.5 tons, 14tons & 22tons hammers depending on test loads and pile lengths. A photo showing HSDPT in progress is shown in Figure 6. The graphical output of CAPWAP performed on the one of the routine pile is shown in Figure 7.

All the tested piles were able to achieve the required test load. Thus, it was proved that testing of long piles is possible with the non destructive testing methods. Correlations validated the results. The methods also helped prove that the piles were of acceptable quality and capacity. There was significant savings in time with the use of High Strain Dynamic testing instead of conventional static load testing.

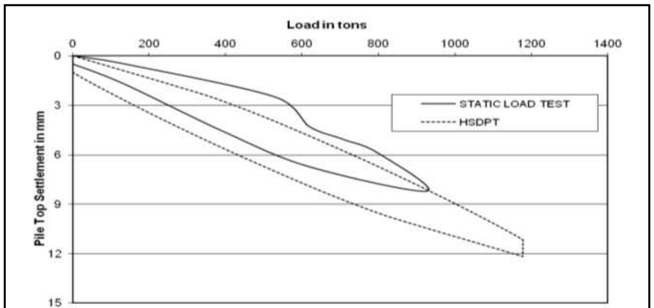


Figure 5 Correlation Study

Figure 6 HSDPT in progress

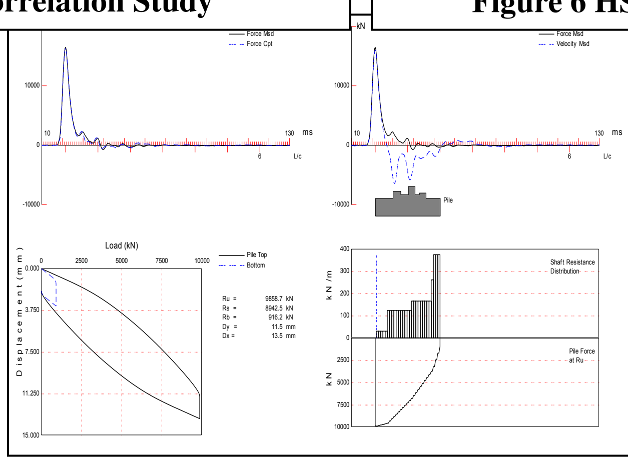


Figure 7 CAPWAP output for typical pile

Testing of Pile Foundations at a site near Vadodara, Gujarat

More than 500 piles were installed at a project site near Vadodara, Gujarat. About 98 sets of the cube test results for the piles passed 7 day tests but failed 28 day tests. The design concrete grade was M30. Results of 9 sets were in the range of 19-22N/mm^2. Results of 36 sets were in the range of 23-25N/mm^2. Results of remaining 53 sets were >25N/mm^2 but <30N/mm^2. Hence, pile concrete quality was questioned and client wanted to evaluate the matter further. The objective was to assess pile foundations due to inconsistent cube test results. The authors were engaged as experts to provide inputs and to help the contractor correctly assess the piles.

Since large number of cubes failed 28 days test, the authors suspected several issues rather than mere focus on concrete quality. Some of the issues were a) Test results depend on proper representative sampling, 2) Handling, 3) Curing, 4) testing procedure, 5) size and shape of mould etc. It was also observed that not all the cubes in a batch had failed but only certain cubes in each batch failed.

Hence, High Strain Dynamic Testing and PIT was suggested to evaluate the concrete and the piles. Thirteen piles were tested using HSDPT followed by CAPWAP. The pile design load was 150 tons and the piles were tested to more than 375 tons to be sure that concrete was acceptable. The CAPWAP showed uniform pile profile and a minimum wave speed of 3400m/sec. Thus, no structural or geotechnical failure was noticed at more than 2.5 times the design load indicating the piles and the concrete was within acceptable range. The maximum stresses in the piles at design load and test load of 375 tons was 5Mpa and 13Mpa. This was much lower than the worst cube test results even assuming concrete was of lower quality. The wave speed although did not indicate any lower quality concrete. The concrete consumption record for the piles indicated overpore and the ratio was 1 to 1.2. Thus under-consumption was not an issue. Static load tests also showed acceptable piles.

Thus all available information and investigations indicated acceptable concrete and acceptable piles. The results of testing were also validated by a reputed European testing company. It was proved failed cube test results does not imply poor pile concrete and vice versa is also true. Cubes test results only provide information about consistency of concrete obtained from batch mix plant and preliminary information on concrete quality. It should be noted that for piles, cube test results are not sufficient to evaluate pile quality but their integrity and capacity are the most important considerations. Inspite of all these supporting facts, client asked contractor to prove that the grade of concrete is M30 up to pile bottom for all the piles. The client then rejected all the piles. This adamant approach by client resulted in huge delays and expenses for the contractor. It also resulted in huge waste of precious natural resources inspite of all the forensic investigations

A Project in Northern India

At a project site in Northern India 1500mm and 1600mm diameter piles were installed. The depth of the piles ranged from 40m to 48m. The proposed construction method was top down construction and after the piling was completed, piles were partially exposed in order to serve as building columns. As described in geotechnical report, the soil at the site consists of alternating layers of clayey silt and sandy silt up to the exploration. A plot indicating variation of SPT along the depth is shown as Figure 8.

The design loads on the piles were 1250tons and 1425tons for 1500mm and 1600mm piles respectively. Since this was a fast track project and only had 54 piles, the contractor was not keen to conduct any testing and representations were made accordingly. An opinion was sought from the first author who recommended that atleast 2 load static or dynamic load tests and few integrity tests should be conducted as there was no such precedence in the region of such large diameter and large ultimate load of 3000 tons or more. Hence it was agreed to conduct tests eventually. . The first author team conducted PIT on all the piles and also three dynamic load tests. From the data, it was apparent that some of the piles have defects. A typical PIT data for a defective pile and confirmation of defect after excavation is shown in Figure 9.

Three piles of 1600mm diameter and two piles of 1500mm diameter were selected for dynamic testing. Four pairs of strain gages and accelerometers were attached to the pile head at 90^0. A 35ton hammer was used for testing. A picture showing HSDPT in progress is shown in Figure 10. All the tested piles were unable to achieve the required test load and settlement of piles were more than 3mm per blow for several blows indicating piles have reached ultimate capacities. Three of the piles did not achieve even design load, also showed major defects, and may have been one of the causes of failures. A third party also validated the CAPWAP test results as the report had huge cost and time implications to the project. A typical graphical output of CAPWAP is shown as Figure 11. A static load test also indicated similar results.

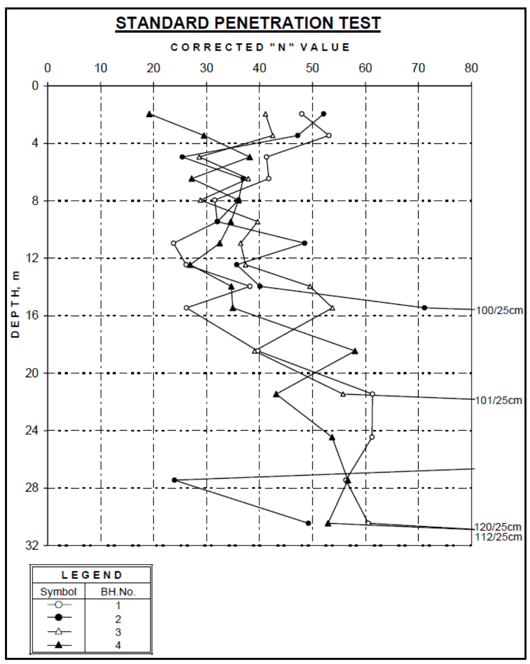


Figure 8 Variation of SPT along the depth

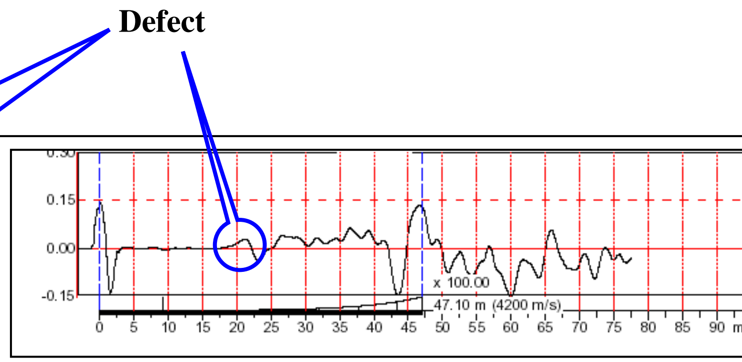


Figure 9 PIT data collected and exposed defect at a site in Northern India

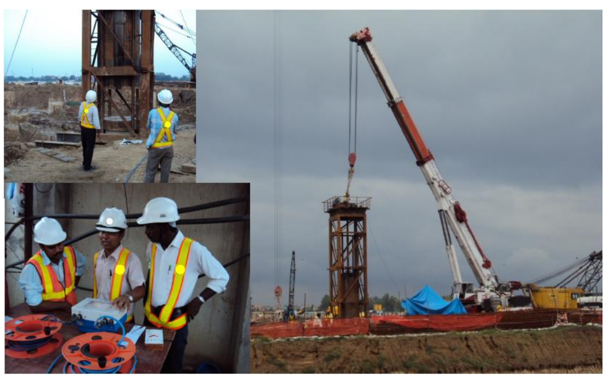


Figure 10 HSDPT using 35ton hammer

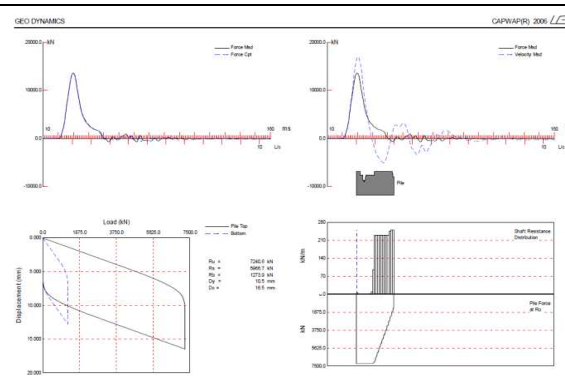


Figure 11 CAPWAP output

Since piles were unable to carry required load, safe load carrying capacity was revised and conservatively considered to be around 450tons – 500tons and the foundation type was changed to piled-raft type. The piles were exposed upto 16m and defects were visible as seen in Figure 9 and matched the PIT, HSDPT findings. . The entire project was like forensic investigation as initially not only the results were in question, eventually it was required to identify even the reasons of failure. Validation by excavation proved the findings and saved a very important structure.

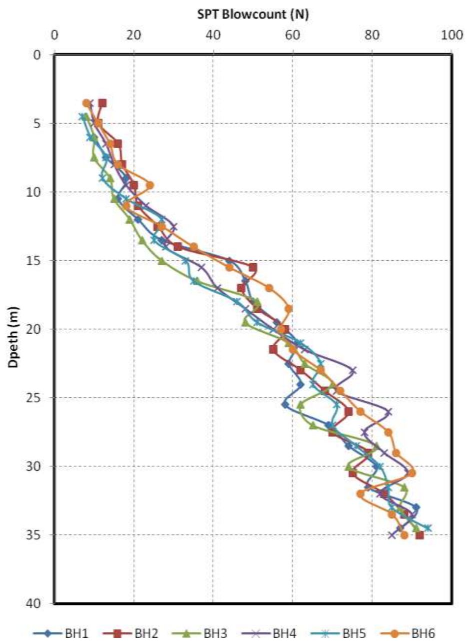
A Project Site in Gujarat

For a project site located in Gujarat, it was proposed to construct residential buildings for an important government organization. . Pile foundations were adopte as the subsurface conditions consist of filled up soil up to upper 4m below which silty sand was encountered up to boring termination depth. In a central portion of the site the depth of fill was found to be as deep as 9m because a presence of a sewer line. The silty sand was loose to medium dense up to around 15m below which the silty sand was dense to very dense. A plot of SPT blowcount along the depth of exploration is presented as Figure 12. The subsurface conditions were similar across the site and soil consistency was increasing along the depth. R.C. bored piles having diameter of 400mm, 500mm and 600mm were installed at the site using truck mounted rig. The lengths of most of the piles were around 18m. The design loads were around 39tons for 400mm, 53tons for 500mm, and 68tons for 600mm piles.

This was again a project where the client had a very limited budget. So it was decided to execute the foundations without any testing. Thus cube tests, bentonite consistency tests, static or dynamic tests, PIT were all removed from the scope of the work.

After completion of piling, in some piles concrete was missing at cut-off level and sound concrete could not be located even after excavating additional 1.5m. The matter was then referred to the authors who suggested PIT on few piles including some piles that were assumed to be acceptable. The PIT results indicated several defective piles and piles with possible soft material at bottom. HSDPT was also conducted on some of the piles and the results confirmed PIT findings with several piles unable to achieve the require test load. The PIT for a typical defective pile is presented in Figure 13 and the CAPWAP results for the same pile are presented in Figure 14.

Almost 30% piles were unable to achieve required test load and most of the piles had defects from 10m-16m depth. Subsequent investigation by the first author proved that truck mounted rotary machines with wash boring is not a suitable equipment for piling in the current form. Since no bentonite consistency was maintained, slush may have remained at the bottom resulting in soft material at pile bottom. It was reported that there were water currents during piling and this might be due to the old sewerage line at 8m-9m and may also have caused subsidence of concrete at top. . The soil profile showed no specific issues and the failure was largely due to poor workmanship and poor selection of machinery for piling. Thus the complete forensic investigations including testing helped the consultants arrive at the possible causes of failure and saved a possible catastrophe.



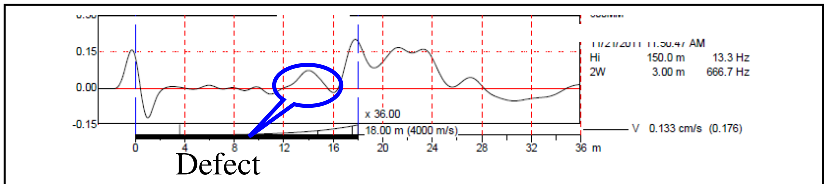


Figure 13 PIT data collected at a site in Gujarat

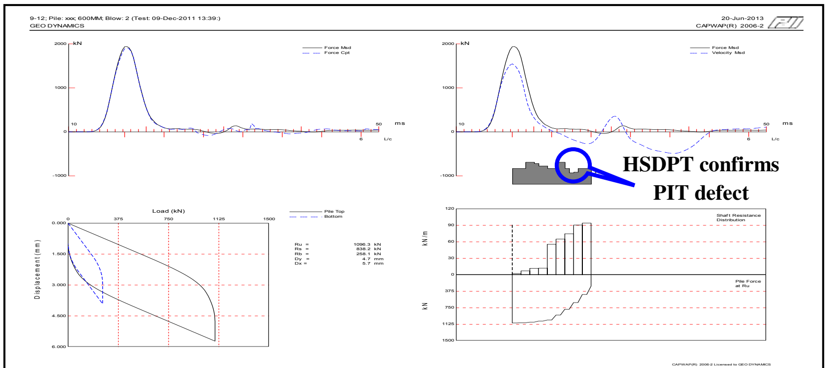


Figure 14 CAPWAP output
HSDPT confirms defect by PIT

Figure 12 SPT blowcount along the depth

A Project Site in Mumbai

At another project site located in Mumbai where rock socketed piles were proposed, the site consists of shallow rock (basalt) which was varying significantly across the site. The top of rock was varying from 4.5m to 10m. The upper soil consists of filled up material up to 2-3m followed by silty sand of varying consistency upto top of the rock. A subsurface profile is presented as Figure 15.

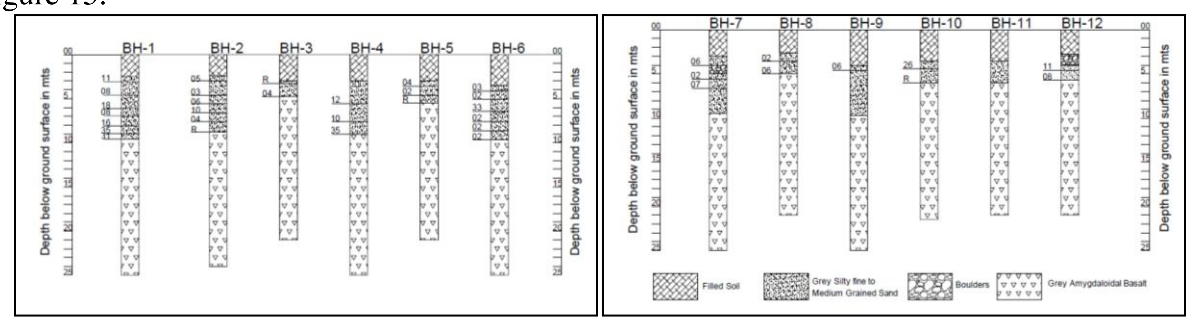


Figure 15 Subsurface profile – A site in Mumbai

Bored concrete rock socketed piles having diameter of 750mm were installed for this 45 storey tower project. The lengths of piles were varying significantly depending on depth of rock. The design load was 280tons and the test load was 420 tons for these piles. The authors were engaged at the jobsite only at the insistence of the consultants as the contractors wanted their own expert. Eventually it was agreed that the authors will perform 50% of the PIT tests. The PIT results showed soft material at pile bottom for several piles. Two such piles is presented as Figure 16. Short and defective piles were also reported. Hence, High Strain Dynamic tests were conducted on 24 piles, and for 15 piles the permanent sets ranged from 4mm to 12mm per blow and the average ultimate capacity ranged from 100 tons to 200 tons against a requirement for 420 tons.

It was then concluded that these piles are not sufficiently socketed or some collapse may have taken place after boring and before concreting and hence may not be able to achieve required capacity.

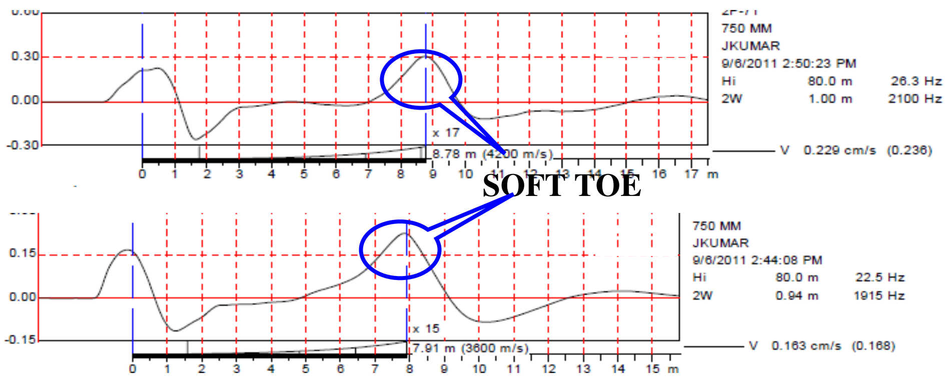


Figure 16 Soft Toe – PIT data for piles tested at a site in Mumbai

The report and findings were contested and it was agreed to core through the centre of the pile. Core test results revealed sand instead of rock. The contractor's consultants then explained that problems in the piles maybe due to soil contamination and the damage was due to Ryznar's index. The Ryznar's index was broadly explained as sudden chemical attack on concrete and subsequent deterioration. This was also contested by the first author and the independent geotechnical engineer employed by the client. It was eventually agreed to install new piles with proper rock socketing at the same site ignoring contamination issues. The additional cost of rectification exceeded Rs. 20 million. The new piles showed good integrity. Due to shortage of space, the design load was revised to 440 tons and all the new piles showed a capacity more than 700 tons with nominal permanent set. Thus forensic investigation helped prove that poor workmanship, inadequate flushing of pile bottom and perhaps termination of piles at inadequate depths during pile installation and was a major reason for failure at the jobsite.

CONCLUDING REMARKS

PIT, HSDPT, CAPWAP analysis etc. are proven tools when it comes to QA/QC practices and for forensic engineering of pile foundations. In all cases the CAPWAP was useful in evaluating actual pile capacities, pile profiles, friction, end bearing components and establishing correlations with static load tests for validation. Thus although CAPWAP theory and analysis is complex, it can also provide solutions when used effectively. There is a huge benefit to the industry if these methods are used properly. However, misuse and abuse of these methods may result in substandard foundations and loss of faith. Thus it is essential that clients and consultants understand the complexity of pile foundation and testing before using them at the project site.

The methods are almost a pre-requisite for forensic investigations in case of pile foundations. It is also important that when such an investigation is under-taken, other data like piling method, soil profile, concrete pour card, source of concrete, structural and geotechnical capacity, and any other allied information in addition to findings from HSDPT, PIT etc. be taken into account before arriving at conclusions.

REFERENCES

Alvarez C., Zuckerman B., and Lemke J. (2006).“Dynamic Pile Analysis Using CAPWAP and Multiple Sensors” ASCE GEO Congress: Atlanta, Georgia.

CAse Pile Wave Analysis Program (CAPWAP) Background Report – 2006.

Eiber, R.J. (1958). “A Preliminary Laboratory Investigation of the Prediction of Static Pile Resistances in Sand”. Master’s Thesis, Case Institute of Technology, Cleveland, Ohio.

Federal Highway Administration Reference Manual – Volume II. April 2006. Design and Construction of Driven Pile Foundations. Publication No. FHWA NHI-05-043.

Hussein, M.H., Goble, G. G., (2004). “A Brief History of the Application of Stress-Wave Theory to Piles”. Current Practices and Future Trends in Deep Foundations, Geotechnical Special Publication No. 125, DiMaggio, J. A., and Hussein, M. H., Eds, American Society of Civil Engineers: Reston, VA; 186-201.

Rausche, F., Robinson, B., and Liang, L., (2000). “Automatic Signal Matching with CAPWAP”. Proceedings of the Sixth International Conference on the Application of Stress-wave Theory to Piles: São Paulo, Brazil; 53-58.

Vaidya Ravikiran & Shah D.L.(2001), “Pile Diagnostics By Low Strain Integrity Testing”, IGC 2001, “The New Millenium Conference”, Indore, India.

Vaidya, R., (2004). “Low Strain Integrity & High Strain Dynamic Testing of Piles - an Indian Overview”. Proceedings of the Seventh International Conference on the Application of Stress Wave Theory to Piles 2004: Kuala Lumpur, Malaysia.

Vaidya, R., Likins, G.E., December (2014). “Guidelines for successful High Strain Dynamic Load Tests & Low Strain Integrity Tests for Bored Piles”. Proceedings of the Indian Geotechnical Conference 2014: Kakinada, India.