Proceedings of the 7th World Congress on Civil, Structural, and Environmental Engineering (CSEE'22)
~~Lisbon, Portugal~~ Virtual Conference – April 10 – 12, 2022
Paper No. ICGRE 173
DOI: 10.11159/icgre22.173

Instrumented Bidirectional Load Test to 157000kN for Deep Foundation Design

Anil Cherian[1]
[1]Strainstall Middle East LLC (James Fisher and Sons plc, United Kingdom), Dubai, United Arab Emirates
Email:anil@strainstall.ae

Abstract - Accurate assessment of the soil-pile structure interaction and distribution of soil resistance along the shaft is complex and indispensable in any civil engineering construction project. The invention and use of the Bi-Directional Static Load Test (BDSLT), a self-balanced biaxial test method, for the high capacity static load testing of deep bored piles gives an innovative and powerful quality control tool to check the initial pile design. BDSLT is now becoming common practice around the Middle East and global construction industry, more convenient, economical, safe and accurate than traditional top-down loading tests. The specially designed, calibrated, sacrificial hydraulic jacks, can be installed at the tip or within the desired stratum at any elevation on the reinforcement cage of a bored pile. It offers the required static loading virtually to any high loads without any overhead load frame or other external reaction systems. An attempt has been made to check the initial pile design values and the results of subsequent BDSLT carriedout for a 2000mm diameter deep foundation pile using bi-directional sacrificial jacks and Geokon embedded vibrating strain gauges to a test load of 157000kN at the proposed mixed-use high-rise tower project in Dubai, United Arab Emirates. The results show that the test pile was capable of sustaining ultimate shaft capacity due to the high shaft friction in the rock strata at a small settlement. This paper describes the installation and instrumentation of the pile, data analysis, and unambiguous information obtained, which can be directly applied to the permanent pile design procedure.

Keywords: Bidirectional, Load test, Pile design, Skin friction, Settlement, Strain gauges

1. Introduction

The design of the pile foundation involves suitable assessment and optimization of key aspects of safety, serviceability, and cost. The United Arab Emirates, the construction hub of the Middle East, has been designing and implementing large-scale high-rise building and infrastructure construction projects for the last three decades. The developments in contemporary geotechnical foundation engineering make it possible to improve pile construction and testing practices. Most of our Geotechnical designers, academic researchers, and consultants have many tools and data available to them, including numerous formulas, computer software, basic and sophisticated laboratory testing, and experience. Frequently, these resources are used to estimate nominal pile parameters, to which a safety resistance factor is applied to determine an allowable pile capacity [1]. However, the advanced BDSLT method of high load testing provides an improved estimate of shaft and bearing resistances to providing an economically viable design to reduce the geotechnical risk in the foundation industry. BDSLT, a self-balanced test, loads the bored pile in compression using sacrificial jacks from the middle/bottom section. As the hydraulic jack expands, the bottom side shear and tip resistance provide reaction for the upper side shear, and top side shear provides reaction for the bottom segment of the pile. In the BDSLT method, side shear and tip resistance components are measured separately [2].

The application of bored shafts and their axial testing is increasing due to their excellence, economic efficiency, and to the trend of high-rise and complex of structures. Foundation quality problems generated due to design flaws, concrete strength deficiency, improper construction due to less skilled workmanship and adverse weather conditions can be minimized to a large extend by using the instrumented ultimate pile load test. Last three decades, the static loading test has advanced into the bidirectional method of testing, which does provide the required information. BDSLT has become common to evaluate the geotechnical capacity of deep foundations, particularly bored and drilled foundations. The bidirectional static load test (BDSLT) has been around since the early 1970s [3-4]. Subsequently, an independent development took place in Brazil [5], which led to an industrial production offered commercially in the Brazil piling industry. Later in the USA, the test was carried out in full scale commercial use by hydraulic jack arrangement placed at or near the pile toe to pursue the bidirectional technique now often referred to it as BDSLT [6-8]. Subsequently, this method was used in different parts of the world to test the capacity of drilling shafts [9-10]. Schmertmann and Hayes have mentioned that bidirectional tests using O-Cell were first performed experimentally and commercially [11]. Poulos and Salem and Fellenius highlight the different characteristics of the tests to help the building foundation industry [12-13]. This testing method was successfully used in the last two decades for cost effective value engineering of foundation piles and barrettes in the Middle East Region [14-18 and 1].The ultimate capacity of a deep foundation is often defined with reference to a pile head settlement. A widely used definition of the ultimate resistance of deep foundations installed in the ground is the load that would cause a deep foundation to settle by an amount equal to 10% of its diameter [19-20]. This method is internationally accepted and referred to in the different standards [21-24].

With an increase in demand for the high-rise building entities that utilize pile construction for their foundation design in Dubai, it is evident that this study will play a key role in the current rapid infrastructure growth. Hence this paper articulates the initial pile design verification with the BDSLT result for the proposed high-rise tower on plot no. 336-210 and 336-299, Dubai, United Arab Emirates.

2. Geological Settings

The geology of the United Arab Emirates, and the Arabian Gulf area, have been substantially influenced by the deposition of marine sediments associated with numerous sea-level changes during the relatively recent geological time [25]. The Geology of the study area is characterized by the presence of the Barzaman Formation, which extends up to 23m depth. The Barzaman formations include reddish brown conglomerates, brecciated dolomitic calcisitites and breccia with clasts of coarse gravel and cobble size of limestone [26]. This formation is overlaid by the reddish brown sandstones, which are extremely weak with localized medium beds of calcilutite breccia. The sandstones are fine to medium sand size with a cementing material that imparts a very inconsistent strength to the rock. The reddish brown sandstones are overlain by a brown to light brown Calcarenite. Localized medium beds of imperfectly laminated or massive Calcarenite with fine to medium clasts are also encountered [14]. Based on the borehole data (BH 01 to BH07), the design parameters (Unconfined Compressive Strength (UCS), Rock Quality Designation (RQD) with depth (m DMD – meter Dubai Municipality Datum) of the pile foundations is summarized in Table 1. Unconfined compressive strength was applied to estimate the ultimate unit shaft resistance at each depth.

Table 1: The general geotechnical parameters.

Layer no.	Description	Elevation (mDMD)	UCS (MPa)	RQD (%)
1	Loose to medium dense silty Sand	+3.36 to -13.00	-	-
2	Very weak to weak moderately fractured Sandstone/Calcarenite	-13.00 to -31.00	0.9	40
3	Weak to moderately weak moderately fractured Conglomerate	-31.00 to -33.50	2.0	40
4	Very weak to weak moderately fractured Siltstone / Calcisiltite	-33.50 to -65.00	1.4	55
5	Weak to moderately weak fractured Siltstone / Calcisiltite	-65.00 to -78.00	2.5	45

3. Methodology

Full-scale BDSLT was performed for one instrumented deep bored concrete pile, viz. TP-1 (Test Pile) using eight sacrificial bidirectional hydraulic jacks embedded between upper and lower steel bearing plates within the pile foundation element (Table 2 and Fig.1). When required hydraulic pressure is applied during testing, the jack assembly can expand in both directions, and loads are applied to the pile in an upward and downward direction. Hydraulic jack positioning is determined based on the geotechnical parameters. This is used as a basis to compute the expected skin friction and end-bearing capacities of the piles. The main purpose of positioning the jack assembly precisely will be to equalize the bi-directional forces in the pile. This will avoid the premature failure of piles in one direction and thereby complete the full-scale load test. This requires not only the knowledge of geotechnical parameters but also the native experience gained from various similar projects. From the initial geotechnical report, unconfined compressive strength (UCS) of a borehole near to pile load test is extracted and the unit shaft friction (kN – kilo Newton) is calculated. From unit shaft friction obtained, the total shaft friction of the pile is calculated and the mid-value of the shaft friction is used as the position of the hydraulic cell assembly [16].

Table 2: Test pile details.

Pile Type	Pile Diameter (mm)	Cut off Level (m DMD)	Toe Level (m DMD)	Working load (kN)	Test load (kN)
TP – 1	2000	-13.09	-78.00	62800	157000
Strain gauge level (m DMD)	-13.60, -17.20, -20.80, -24.40, -28.00, -31.60, -35.20, -38.80, -42.40, -46.00, -49.60, -53.20, -59.80, -62.30, -64.80, -67.30, -69.80, -72.30, -74.80, -77.50 and jack level at -56.50				

The instrumentation of the pile includes twenty levels of Geokon vibrating wire concrete embedded strain gauges, hydraulics jacks, tell-tale rod extensometers in conjunction with displacement transducers. Vibrating wire strain gauges embedded at different depths are to measure strain during load application, and to calculate the shaft friction and load distribution. Tell-tales extensometers as well as displacement transducers measure displacement at cell top and cell bottom. Pile top movement under an applied load will be measured directly from the shaft top using two displacement transducers that are installed at the testing platform level (Fig.1 and Fig. 2). Once the required concrete strength is attained, generally 14 days after casting or as per the specification, the pile test will be started. During the application of load, the hydraulic cell begins working in the opposite direction, upward against upper skin friction and downward against lower skin friction and base resistance. The test is considered to be complete after reaching the ultimate capacity above or below the hydraulic cell or upon reaching the maximum capacity of the hydraulic cells. The load increments were applied as specified in the loading schedule and each successive load increment was held constant by adjusting the hydraulic jack pressure until the settlement criteria were met. Data acquisition of all embedded instruments was connected to a data logger and a laptop allowing the data to be recorded and stored automatically at stipulated intervals and displayed in real-time. The unit shaft resistance obtained from the load test results was compared with the initial ground test parameters using Eurocode 7 [27] procedures to understand the soil-pile interaction process.

Fig. 1: BDSLT pile installation.

Fig.2: BDSLT test setup.

4. Results and Discussion

4.1. Settlement and shaft friction

The bidirectional load displacement data obtained from the pile test is analysed to obtain the required Equivalent Top-Loading Curve (ETL). The ETL curve (Fig. 3) is an assessment of the applied load-displacement performance of the test pile which would result from a traditional top-loading static compression test. Since bi-directional test loads are applied at some depth within the foundation element, such load-displacement relationships are not measured but must be constructed using the assumptions [8]. BDSLT site data are typically presented in a butterfly-shaped plot giving load-displacement behaviour of the pile in both directions, governed by upper shaft, lower shaft and base resistances developed during the test. The jack movement data obtained from the test is analysed using an equivalent top loading method to identify the elastic settlement curve [28-29]. The equivalent top load curve is constructed by selecting a displacement value from the tests data. This selected value will be used for both the top and bottom cells because the pile is assumed to be rigid. To obtain the load for both up and down curves, draw a line from the selected value until it meets the load displacement curve. Add the corresponding loads to obtain the total load which is equivalent to the load on the pile head. Continue the procedures to construct the equivalent top-load curve and modify the curve by including the elastic shortening of the pile foundation [8].

Fig. 3: Settlement values obtained from BDSLT.

The settlement values (Fig 3) obtained during the test at working load were 17.60mm and the ultimate load was 38.60mm respectively. The increase of settlement values in the ultimate load is perhaps due to the soil types, varying density, and implies that the load-carrying capacity is dominated by shaft resistance. It is difficult to estimate the possible differential settlement undergoing various loading forces after the completion of the superstructure [30]. The inferences of settlement from the pile load test data may be conservative, although it must be noted that the general foundation settlement behaviour is dependent on the individual pile characteristics as well as the ground conditions within the zone of influence of the structure. Therefore, during the design of this foundation, the side resistance of the pile was the only capacity criterion accounted for in the overall design, and the settlement value was not considered. The mobilized shaft friction obtained during the test from strain gauge readings at the ultimate load and ground test is presented in Table 3.

Table 3: Mobilized unit shaft friction from load test and ground test.

Strain gauge level (from pile top to bottom)	Stratum	Load test (at 157000 kN)	Ground test
		kPa	kPa
1 to 2	Loose to medium dense silty Sand	5	237
2 to 3	Very weak to weak moderately fractured Sandstone/Calcarenite	7	
3 to 4		8	
4 to 5		10	
5 to 6		12	
6 to 7	Weak to moderately weak moderately fractured Conglomerate	38	353
7 to 8	Very weak to weak moderately fractured Siltstone / Calcisiltite	22	296
8 to 9		463	
9 to 10		292	
10 to 11		280	
11 to 12		1193	
12 to Jack		1074	
13 to Jack		1077	
13 to 14		652	
14 to 15		803	
15 to 16	Weak to moderately weak fractured Siltstone / Calcisiltite	274	395
16 to 17		1073	
17 to 18		329	
18 to 19		363	
19 to 20		40	

4.2. Load transfer mechanism

The pile-element relation is called the load-transfer function (t - z curve), which is a mathematical expression of the load and movement relation [31]. All load-transfer functions are curves that either rises steeply at first and become less steep as the movement increases or reduce after having reached a peak at a certain movement. Occasionally, a shaft resistance seems constant after having reached a maximum value and thus demonstrating a plastic response. Nevertheless, the load-movement behavior to shaft resistance along with a pile segment, after an initial movement, is only rarely plastic [31].

The axial pile performance of deep foundation was analyzed using the relationship between mobilized soil- pile shear transfer and pile vertical deflection/settlement (t-z curve) of the bored pile during stages of loading. There are numerous different methods for interpreting this kind of axial load transfer and pile displacement curves [32]. The most common approach is by demonstrating the mobilization of shaft friction displayed as a set of springs distributed along the pile shaft, and the axial elastic stiffness of the pile [33]. The distribution of stiffness of both the pile and soil, pile geometry, and soil distribution are all influential factors. The construction of t-z analysis, by using the unit resistance values based on strain gauge data and settlement from the BDSLT data, describes the soil-pile behavior over the entire length of the pile. In order to estimate the load transfer mechanism, calculations of the pile settlement can be performed using the pile settlement as a function of unit shaft friction. The plot obtained for the test pile is given in Fig.4.

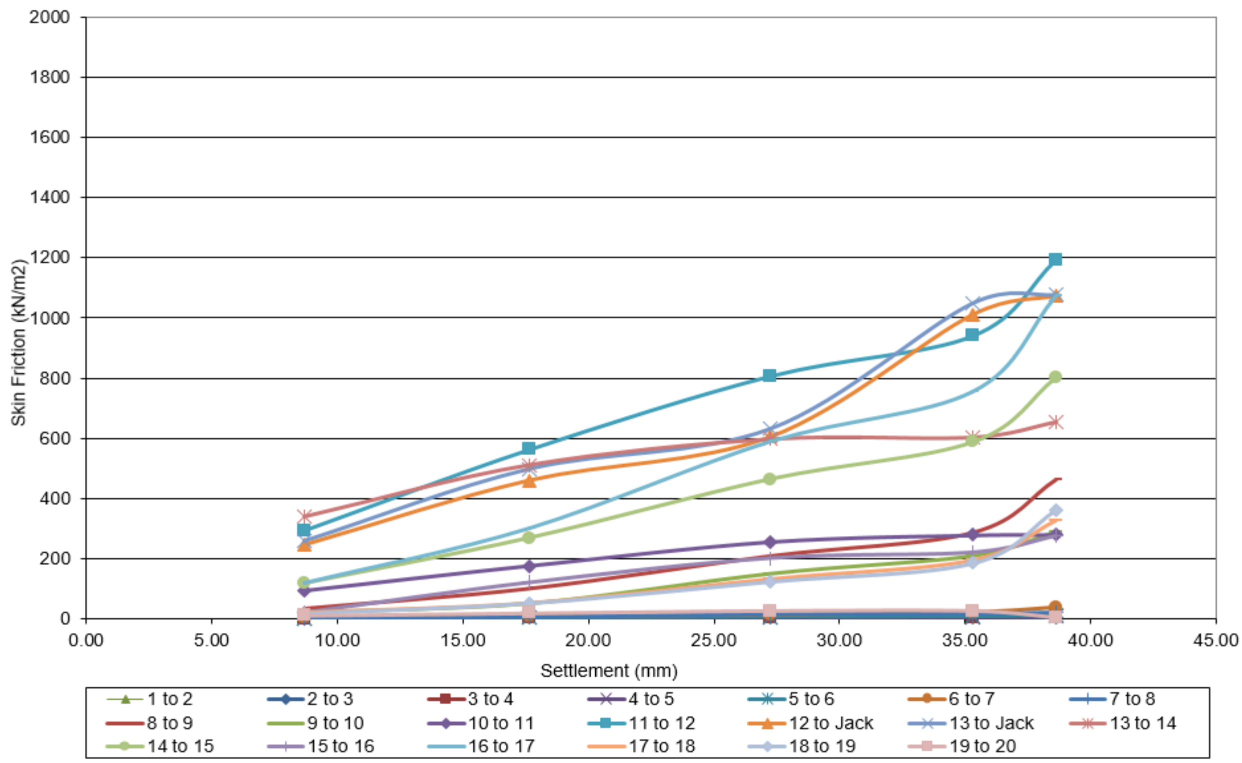

Fig.4: Skin friction – settlement (t-z) plot from load test

The maximum average unit skin resistance mobilized from the pile load test to 1193 kPa and at a normalized pile settlement of 38.60mm (Fig 4). The unit shaft friction kept increasing linearly and not reached its maximum stress, even at the ultimate test load. Based on the t-z curve, it is suggested that plastic deformation did not reach along the pile shaft at different loads. It can be due to the fact that the majority of the load is consumed by the deeper stiff layers. This behaviour can be a result of a stiff pile and partly dependent on a minor pile settlement as observed from the load tests. This indicates that the test piles are not fully mobilized and the settlement is within the general permissible limit of less than 2% of the pile diameter at the working load [16, 34].

The t-z functions analysis of the results of the load test enables the settlement of the foundation supported on the pile to be determined. This ultimately eliminates the need for a theoretical assessment of capacity and applying some factor of safety to arrive at a presumed safe working load that may or may not give an acceptable level of settlement, which are removed from the test result that the pile toe resistance is very small. The load-distribution analysis will enable an estimate on the long-term settlement behaviour of a foundation supported on a similar pile for which the analysis of the pile response would have to include the effect of adjacent foundation and other related influencing factors [35]. Moreover, the analysis will aid in the sectioning and execution of a suitable length and diameter and excavation around the piles or back-filling to the site, etc. In order to assess the performance of the test piles further and to derive suitable shaft friction design values, optimization of pile design was carriedout using Eurocode 7 procedure before execution of production piles of the project.

4.3.Design shaft resistance

The introduction of Eurocode in the foundation testing allows for the application of modern unified technological tools for the design of structures and different combinations of loads with the application of all types of construction materials. It applies the principles of ultimate limit states for analysis of shaft bearing capacity, which is, factoring resistances and loads separately [36]. In this study, the shaft capacity of a single pile that is subjected to compression is calculated using Eurocode 7. Eurocode harmonises the geotechnical design with structural design through the introduction of a common design method and provide a flexible code through the introduction of different design approaches to use partial material factors or partial resistance factors, and therefore can be applied to different national and international design practices.

Eurocode 7 describes the procedures for obtaining the characteristic compressive resistance of a pile [37]:

a) Directly from the load test

b) By calculation from profiles of ground test results from the soil report

The design pile resistances derivation requires applying the resistance partial factors to the characteristic values. Since only one test was carried out, the obtained unit shaft friction parameters from a maximum load of 250% have been considered in the evaluations and a correlation factor of $\xi 1=1.3$. The combinations of partial factor values that should be used for Design Approach I are as follows:

DAI.CI: A1 + M1 +R1
DAI.C2: A2 + M1 or M2 + R4

The combinations of sets of partial factor values that ought to be used for Design Approach 2 are as follows:

DA2: A1 + M1 + R2
Whereas Design Approach 3 is computed as:
DA3: A1 + M2 + R3

where:
A1/A2 denotes partial factors on action.
M1/M2 denotes partial factors for soil parameters.
R1/R2/R3/R4 denotes partial factors for resistance.

Characteristic resistance obtained using a partial factor of 1.30 was calculated based on shaft friction within the rock layers of the pile embedded. Based on the results obtained from the load test and the ground result, the recommended design shaft friction values are calculated by subtracting half of the standard deviation from the average value of the load test and ground test results (Table 4).

Table 4: Adopted design unit shaft friction after BDSLT

<table>
<tr><th rowspan="2">Strain gauge level (from top to bottom)</th><th rowspan="2">Stratum</th><th>Load test (at 157000 kN)</th><th>Ground test based Eurocode</th><th>Recommended value</th></tr>
<tr><th>kPa</th><th>kPa</th><th>kPa</th></tr>
<tr><td>1 to 2</td><td>Loose to medium dense silty Sand</td><td>5</td><td rowspan="3">182</td><td rowspan="3">94</td></tr>
<tr><td>2 to 3</td><td rowspan="2"></td><td>7</td></tr>
<tr><td>3 to 4</td><td>8</td></tr>
</table>

4 to 5	Very weak to weak moderately fractured Sandstone/Calcarenite	10		
5 to 6		12		
6 to 7	Weak to moderately weak moderately fractured Conglomerate	38	271	296
7 to 8	Very weak to weak moderately fractured Siltstone / Calcisiltite	22	227	262
8 to 9		463		
9 to 10		292		
10 to 11		280		
11 to 12		1193		
12 to Jack		1074		
13 to Jack		1077		
13 to 14		652		
14 to 15		803		
15 to 16	Weak to moderately weak fractured Siltstone / Calcisiltite	274	304	318
16 to 17		1073		
17 to 18		329		
18 to 19		363		
19 to 20		40		

The initial test pile was mainly performed prior to the installation of the production piles to check the pile capacity, construction quality and the performance of the foundations. A linear increase of unit skin friction values was observed and does not display evidence of developing geotechnical failure, giving a comfortable margin of safety. This indicates that the pile can be still loaded to mobilize ultimate skin friction resistance along the complete shaft length without any geotechnical risk. The shaft friction obtained from the load test was more than adequate to resist loads in excess of the pile working load and hence not able to mobilize any tip resistance. Since the skin friction in the upper and lower part of the shaft segment does not seem to have been fully mobilized during a load test, it was proposed that the ground test data in that location be used during the final design. The results of the preliminary pile load testing program were compared with those obtained from the ground test. It can be concluded that the load test can appropriately represent the characteristics of soil strata and the side resistances determined are larger than the design values adopted. On the basis of load test data, recommended unit skin friction values were used for the final design of production piles.

Table 5: Revised pile design used in the project

Pile ID	Diameter (mm)	Cutoff level (m)	Toe level (m)	Pile capacity (kN)
TP-1	2000	-13.09	-57.895	66694

Based on the above result, for a compression load of 66694 kN for the piles with a length of 51.91m is found to be sufficient for the foundation design. Accordingly, the piles were redesigned with a length reduction of 20% and were implemented in the project (Table 5). BDSLT results and subsequent analysis reconfirmed the pile length reduction of 13.0m to provide a suitable value engineering design by saving in foundation costs by reducing drilling costs, material costs, construction time, labor and less expensive to load test. The results obtained from the load test were accurate as there was no indication of pile defects due to poor construction and quality control.

5. Conclusions and suggested future research

The effective performance of this full-scale instrumented load test provides the confirmation of soil characteristics and the pile-soil interaction for a reliable and economical foundation design. Load test results indicate that the pile design can be optimized in length up to 20%, reducing the current pile length from 64.91m to 51.91m deep. This study has proven that instrumented BDSLT method can be effectively performed in any part of the world to provide a quality control tool of the design resistance parameters. The results derived from the testing have to lead to a reassessment of the original pile design to benefit future stakeholders in designing economically viable high-rise building projects by changing the pile geometry. The results of this instrumented BDSLT on a large bored pile emphasized the necessity of using preliminary load tests for efficient design and an excellent model for such prestigious future high-rise building projects in the region. Further studies on similar high capacity fully instrumented BDSLT in different geotechnical conditions will be a reliable, cost-effective tool to improve confidence in the deep foundation design.

Acknowledgement

The author is grateful to Strainstall Middle East LLC (James Fisher and Sons plc, United Kingdom), Dubai, United Arab Emirates for their continued support and encouragement.

References

[1] A. Cherian, "Geotechnical evaluation of multi-layered Simsima Limestone using Bidirectional Static load test," *J. Geo. Soc Ind., vol.*97,pp.670-674, 2021a.

[2] J.H.Schmertmann, J.A.Hayes, A. John , M. Thomas and J.O. Osterberg, "O-Cell testing case histories demonstrate the importance of bored pile (drilled shaft) construction technique," in Proceedings of the fourth international conference on case histories. Missouri,1998.

[3] G.L.Gibson and D.W. Devenny, "Concrete to bedrock testing by jacking from the bottom of a borehole," *Can. Geotech J.*, 10, pp. 304-306, 1973.

[4] J.M.Amir, "Interpretation of load tests on piles in rock," in Proceedings of the 7th Asian Regional Conference on Soil Mechanics and Foundation Engineering, Haifa, 1983, pp 235-238.

[5] P.C.A.Elisio, "Celula Expansiva Hidrodinamica – Uma nova maneira de executar provas de carga (Hydrodynamic expansive cell. A new way to perform loading tests) ," Independent publisher, Belo Horizonte, Minas Gerais State, Brazil, 1983.

[6] J.O.Osterberg, "A New Simplified Method for Load Testing Drilled Shafts," Foun Drill Vol. XXIII ADSC, p 9, 1984.

[7] J.O.Osterberg, "New Load Cell Testing Device," in Proceedings of the 14th Annual Conference. Deep Foundations Institute, pp. 17 – 28, 1989.

[8] J.O.Osterberg, "The Osterberg load test method for bored and driven piles- The first ten year," in Proceedings of the Seventh International Conference and Exhibition on Piling and Deep Foundations, Vienna, Austria, 1989.

[9] J.W.Goodwin, "Bi-Directional Load Testing of Shafts to 6000 Tons," *Am. Soc. of Civil. Eng. (ASCE) Geot Sp Publ*, vol.58, p 204, 1993.

[10] B.J.Meyer and P.R.Shade, "Touchdown for the O-cell Test," *Civil. Eng.* Vol.65, 45-57, 1995.

[11] J.H.Schmertmann and J.A.Hayes, "The Osterberg cell and bored pile testing – a symbiosis," Proceedings, 3rd IGEC, Cairo, Egypt,1997.

[12] H.G.Poulos, "Tall building foundations: design methods and applications," Innov Infra Solu., vol.1, pp.1-51, 2016.

[13] H.Salem and B.H. Fellenius, "Bidirectional pile testing - what to expect," in Proceedings of the 70th Annual Canadian Geotechnical Conference, Ottawa, 2017.

[14] A.Cherian, "Value engineering of foundation design using Bidirectional Static Load Test (BDSLT): A Case Study from Dubai, United Arab Emirates," *Int Jour Ear Sci and Eng.*, vol.11 pp.270-273, 2018.

[15] A. Cherian, " Geotechnical and geological aspects of Structural Health Monitoring in high-rise buildings ," *J Ind Geoph Union*, vol.24, pp. 10-24 . 2020a.

[16] A.Cherian, "Assessment of pile capacity using Bidirectional Static Load Test (BDSLT) ," *Ind Geot J* ., vol. 51, pp.369-375, 2020b.

[17] A. Cherian , "Characterization of Simsima Limestone for foundation design in Qatar: A Case Study *J Rock Mech Tun Tech* ," vol.26 pp.109-122, 2020c.

[18] A.Cherian, "Bidirectional Static load test using instrumented pile: An innovative testing method in the construction industry," in Proceedings of the 7th, ICRAGEE (Seismic Design and Performance), India, pp. 361-364 , 2021b.

[19] British Standards Institution, "Code of practice for foundations," BS8004, London, 1986.

[20] R.Salgado R, "The engineering of foundation," 1st Ed. McGraw-Hill, New York, 2008.

[21] ASTM D8169, "Standard test methods for deep foundations under Bi-Directional Static Axial Compressive Load," ASTM International, USA, 2018.

[22] ICE, "Manual of Geotechnical Engineering," 1458-1460, 2012.

[23] Federation of Piling Specialists, "Handbook on pile load testing. Federation of Piling Specialists," Beckenham, 2006.

[24] IRC 78, "Standard specifications and code of practice for road bridges, Section VII Parts 1 and 2, Foundations and Substructure," 2014.

[25] H.G.Poulos, "A review of geological and geotechnical features of some Middle Eastern countries," *Inn Infra Sol*., vol.3, pp.45-58, 2018.

[26] S.Macklin and A. Gaba "Engineering in the Barzaman Formation, Coastal Dubai, UAE," *Civil Eng J.*, vol.162, pp. 18-24, 2009.

[27] Eurocode 7, "Geotechnical design: The European Union Report no. EUR 26227 EN doi: 10.2788/3398," 2013.

[28] M.England, "Review of methods of analysis of test results from bi- directional static load tests," in Proceedings of Deep Foundations on Bored and Auger Piles, Taylor & Francis, pp 235–239, 2009.

[29] S.Hoyoung, B.M.Rozbeh and D.L. William, "Assessment of methods for construction of an equivalent top loading curve from O-cell test data," Soil and Found, vol. 56, pp. 889–903, 2016.

[30] A. Mandolini, G.Russo, G and C.Viggiani, "Pile foundations: Experimental investigations, analysis and design," *Ground. Eng.*, vol.38(9), pp.34-35, 2005.

[31] B.H.Fellenius and M.M. Rahman, "Load-movement Response by t-z and q-z Functions," *Geot Eng J SEAGS and AGSSEA*, vol. 50 pp.11-19, 2019.

[32] The American Petroleum Institute, "Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms," 22nd Ed. Washington DC, USA, 2007.

[33] K.Karlsrud, "Ultimate shaft friction and load-displacement response of axially loaded piles in clay based on instrumented pile tests," *J Geot and Geoenv Eng*., vol.140, pp. 04014074-1-16, 2014.

[34] M.Tomlinson and J. Woodward, "Pile design and construction practice," Taylor and Francis, London, 2008.

[35] B.H.Fellenius, "The unified design of piled foundations ," The Sven Hansbo Lecture. Geotechnics for Sustainable Infrastructure Development – Geotec Hanoi, edited by Phung Duc Long, Hanoi, 2016.

[36] B.H.Fellenius, "Piled foundation design as reflected in codes and standards," in Proceedings of the DFI-EFFC International Conference on Piling and Deep Foundations, Stockholm, May 21-23, pp. 1013-1030, 2014.

[37] B.Wrana, "Pile load capacity – calculation methods," *Studia Geote et Mech*., vol.37, pp. 83-93, 2015.