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# Evaluation of Load-Settlement Probe Mechanisms: A Review

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**ABSTRACT**

Review of studies on mechanisms of load-settlement study was carried out along the line of laboratory, semi-laboratory and field in-situ bearing capacity probes. It was observed that the loading mechanisms differ from direct load to indirect load application through lever arm to jack/reaction frames. Application of loading through jack was observed to be the most common, but and can only apply and sustain constant loading for short period of time, which do not allowed enough time for consolidation settlement in cases of soil bases of clayey nature. Although, field load bearing tests still stand as the most reliable method of estimating bearing capacity and settlement for shallow foundations, but the current mechanisms use heavy duty jack/reaction frames to apply load, which only sustains the loadings for short period of time. This will not allow pore pressure dissipation in saturated clay soils and can therefore, not be used in saturated clay deposits.

**Keywords:** *Bearing capacity, Bearing probe, laboratory bearing capacity, in-situ bearing capacity, Settlement*

## 1.0 INTRODUCTION

Foundation is an integral part of a structure that is directly in contact with the soil. The foundations of most civil engineering structure are permanently attached or placed in direct contact with the soil, transferring the superstructure loads to the subsoil, in order to maintain stability of the structure (Geo publication, 2006). In foundation design process, bearing capacity and settlement are two main criteria that govern the design process, so that safety and serviceability requirements can be achieved (Shahin, 2014). They are also considered in deciding the type and depth of footing to be adopted for the intended structure.

The conventional method, used in evaluating allowable bearing capacities of soil deposits is to excavate the soil to required depth, considering the proposed depth, for placement of foundation and depth to seat of settlement. Disturbed and undisturbed soils are then collected and transferred to the laboratory for requisite tests to obtain the parameters used to obtain the bearing capacities and settlement. There is high degree of uncertainties associated with laboratory testing procedures, and errors due to simplified transformation models developed for estimation of bearing capacity and settlement of shallow foundations (Teodoru and Toma, 2009; Vitale and Skuodis, 2013; Guil and Ceylanoglu, 2016; Mohanty and Kumar 2018). These uncertainties have resulted to development of Field in-situ tests which provides information of a soil at the natural state, while maintaining its moisture conditions and allows for identification and characterization of the soil in estimating the strength and deformation parameters and the load history directly on site. The results obtained here can be used directly in design (Kozlowski and Niemczynski, 2016). Field plate load test is considered as one of the most suitable techniques used to obtain realistic load-settlement response of foundations resting on soil/rock.

Plate load test is an in-situ test conducted on site to determine the bearing capacity and settlement of shallow foundations. BS 1377-9 (1990) and ASTM D1194-94, both describe plate load test as one of the reliable testing methods available for determining in-situ strength parameters of soils.

Bearing capacity and settlement are the key parameter in design of shallow foundations. It is an important parameter used in deciding the size and depth of foundations. Various types of damages can occur to superstructures, resulting from problems associated with excessive foundation settlements, which include cracks, tilts, differential settlements or displacements. In shallow foundations design, the main components of settlements are immediate and consolidation settlements. It is a common knowledge that there is difficulty in correctly predicting bearing capacity and settlement of foundations due to inconveniences in sampling operations (Degroot *et al.*, 2005). Therefore, the testing of the mechanical properties of soil under field conditions is most authentic, because of the absence of distortions, which are connected with collection of samples and their transportation. The procedure associated with the conventional plate loading test mechanisms, only allows measurement of immediate settlement. But in clayey soils consolidation settlement account for most of the settlement. In clayey soils, pore water dissipation is very slow which results in slow hydraulic conductivity (Terzahi and Peak, 1948). This work is therefore intended to review some available literature on the performance of some existing load bearing mechanism at laboratory, semi-laboratory and field test levels.

## 2.0 FIELD PLATE LOAD TEST

Numerous studies have been carried using models and large scale foundations, in-situ, to determine the load-settlement relationship of foundations. Plate or footing loading tests on residual homogeneous, cohesive-frictional soil was conducted by (Consoli *et al.*, 1998). The aim of their research was to determine effect of footing size and shape on settlements and bearing capacity of vertically loaded shallow foundations, resting on uniform layer of lightly cemented residual soil from basalt. The tests were conducted using rigid circular steel plates of different diameters (0.30, 0.45, and 0.60m) and rigid square concrete footings of various sizes (0.40, 0.70, and 1.00m). To study the influence of size, all the footings were cast in a prepared excavation at a depth of 1.20m below the ground level. Because the upper 1.20m of soil was removed over a large area in the testing site, there was no embedment effect on the footing response. Load was applied through a jack and Kent ledge and measured using a calibrated load cell. Four dial gauges with divisions of 0.01 and 50mm travel were used for settlement measurement. The gauges were fixed to a reference beam and supported on rods, installed outside the test pits. The load was applied in cumulative equal increments of not more than 1/10 of the estimated ultimate bearing capacity. Effect of size of the loaded area in the measured settlement and bearing capacity was shown to be negligible. Circular and square elements demonstrated similar behaviour during initial loading, but small differences were observed at large strains near the ultimate bearing capacity. Only immediate settlement was taken into account in the study.

Nwokediuko *et al.* (2019) carried out laboratory test, and then plate load test on three different sites to determine load-settlement characteristics of foundation on tropical red soil in southern Nigeria. Reaction plate load test using square plate of 600mm by 600mm and 25 mm thickness was placed on 20 tons capacity hydraulic jack and the loading was carried out incrementally from 20kN to a maximum of 500kN and deformation was measured using dial gauges. Settlements were recorded at regular intervals for site A, B and C as 8.79, 12.77 and 22.85 mm respectively, while laboratory test was carried out to obtain index and the strength properties of the base soil. From their findings, load-settlement curve for sites A and B correspond to the cohesive soils and site C correspond to cohessionless soil. Plate load test was compare with finite element analysis using plaxis 2D. The maximum settlement predicted by finite element was 12.30mm, whereas that obtained from field was 12.77mm, showing that index and strength properties can be used in predicting reliably, settlement characteristics of soil in a terrain where conducting plate load test on field is difficult.

Mohammed (2013) studied the allowable bearing capacity of soil using plate bearing test during a diesel power plant project in Al-diwaniyah city. The test was carried out using a circular plate of diameter of 0.61m and thickness of 30mm, a reaction load device, and hydraulic jack assemblage, dial gauges and loading gradually up to a maximum load of 410kN/m$^2$. The load was applied to the plate via a factory calibrated hydraulic cell and a hydraulic jack. The readings of loading was carried out and subsequently, the deformations. The time before the next increment loading was not more than 15min. Results of the investigation showed that increase in the elapse time for static applied pressure causes increase in settlement up to 15min and the settlement was faster in first few seconds after each new load increment. the limitations of the study is that, the test was quick to complete, indicating that there was no enough time for the settlement and pore water to dissipate from the soil to allow consolidation to take place.

Warmate and Nwankwola (2014) carried out an evaluation of plate load test on a partially cohesive clay soil in Calabar, South eastern Nigeria, to determine the in-situ safe bearing capacity of the soil. Four plate load tests was conducted on 1.0m pit using circular steel plate of thickness and diameter of 25 and 30cm respectively. A reaction load was placed on 700bar hydraulic jack that was directly placed on the test plate and a sitting load of 7kN/m$^2$. The loading was carried out incrementally from 50 kPa to the maximum of 350kPa. Each load was kept for less than 1hr before increment. The load increment continued untill settlement of 25mm was obtained. At the end of the test, the result obtained congruent with the soil compressive strength. The index properties correlates reasonably with the load-settlement curve obtained from test. The limitation of the test is that during the test, load increments was relatively fast, which does not allow consolidation settlements to take place before the next loading. Also the use of hydraulic jack does not allow sustaining large loading for a long time.

Barnard and Heymann (2015) used conventional and modified plate load tests to determine effect of bedding errors on the accuracy of plate load tests results. The test arrangement involved placing the test plate on the ground surface to measure the settlement of soil in contact between the plate and the rough ground. The experimental was conducted in a farm at University of Pretoria, South Africa. During the three different tests, different surface preparation methods were used before each of the test. These are firstly, the use of only hand tools to level the test area before placement of test plate, secondly, a thin layer of well-graded sand was place before placement of test plate, and thirdly, a thin layer of Plaster of Paris before placement of test plate. For each surface preparation methods, two tests were performed. The surface roughness was measured by means of a high-precision laser measuring system. The test area was scanned with the laser measuring system before and after each test in order to evaluate the change in surface roughness. In addition, a modified plate load test was designed to eliminate effect of bedding errors that occur during these tests by using telescopic probes to measure the relative displacement at two points below the center of the plate. The stiffness values, determined from the vertical displacement of the plate, were compared with the internal stiffness values determined with the telescopic probes, as well as with the stiffness from Continuous Surface Wave (CSW) measurements. The main components of the plate load test used, included a 1.3 ton steel reaction beam together with four grouted anchors, a hydraulic jack of 200 kN load capacity, a loading sequence of 8, 24 and 100kN. For the 450mm diameter plate, these loads resulted in 50 150 and 628kPa contact pressures respectively. Results from the study demonstrated that bedding errors have significant effect on soil stiffness values when external measurements are used to measure settlement of the plate. Such plate load tests can result in stiffness values of up to 50% lower than values inferred from seismic tests. In addition, measurements made using telescopic probes were discovered to be superior to those from external measurements, especially at small and intermediate strain levels. They however recommended the methods for use when accurate stiffness values are required.

In-situ plate load test with three different plate dimensions was carried out by Araujo *et al*. (2017) on sand deposit, to determine the effect of plate dimension on bearing capacity and settlement. A circular plate of 0.3, 0.5 and 0.8m placed at the depth of 0.5m, and hydraulic jack, placed below ground surface were used to perform the test. The results showed that for same applied stress or load, the settlement values as well as load increases as the plate dimensions increases, although, this increase is nonlinear, the while bearing capacity obtained, using Leonard's method showed a decreasing trend with increase in plate dimension as against B/30 and Terzaghi's methods. The Allowable bearing capacity obtained from the three methods showed decrease with increase in plate size. The limitation of the test methods is that all the three methods used only determined immediate settlement, because the procedures were fast.

Various plate load test and laboratory test methods over 15 years were compiled by Tunse *et al*. (2016) to provide data base for different types of soil for various foundation design problems by Maharashtra Engineering Research Institute, Nashik, Maharashtra, India. All the tests were conducted in pits. The setups were gradually loaded with 1kg/cm$^2$, for the clayey soil, loading interval of 0.5kg/cm$^2$ was allowed. In the case of sandy soils the specific load was re-extricated to 2kg/cm$^2$ and settlement was measured for that material and the relationship between ultimate bearing capacity and settlement for specific load has been established. The settlement of the soil for each loading was recorded using the three methods of plate load test, namely; i) gravity, ii) reaction load method and iii) truss and anchoring method. At the end of the analysis of the results, reaction load method was found to be more convenient, compared to the other two methods.

Kadiri and Bytyci (2014) conducted an investigation into soil properties using in-situ tests for foundation of a tank, design in Prizren town. In their study, static penetration test, Standard Penetration Test (SPT) and Plate Load Test (PLT) were carried out to evaluate properties of the soil. Field static penetration test was used to measure resistance to penetration of cone under the influence of static force, using indentation force by means of hydraulic pressures, hollow tube of 36mm and a steel rod of 15mm. SPT was used to advance the investigation of soil boring into a deeper level to obtained approximate measure of the dynamic soil resistance as well as disturbed drive samples using a split barrel and a hammer of weight weighing 63.5kg. Plate Load Test make uses of a light hydraulic jack and a circular steel plate of 305mm diameter. The load was applied to the plate in an incremental order. During application of the load, settlement of the plate was observed from the dial gauge. The test continued until 25mm settlement was achieved. The results of the study showed that plate load test predicts good bearing capacity of soil compare to other types of tests and is more economical in term of cost and time. The limitation of the test was that it was quick to complete and does not allowed for 24 hr monitoring of settlement for each applied load.

Viana (2001) conducted footing load and plate load tests on a residual soil in other to predict settlement of shallow foundation. A reinforce concrete foundation of 1.2m diameter and 0.5m thick was loaded from kentiledge by a hydraulic jack. The 140 tons kentiledge was provided by a water tank of 11.2m diameter, supported by four steel beams, resting on concrete bases, placed 4.6m from the centre of the test area. A separate beam was used for loading, and dial gauge to measure settlement of the concrete foundation. Short calibrated staffs, made from 20mm square steel tubes, welded to a small base plate was founded on small pads of mortar. A precise surveyor’s level was placed in a pit so that its collimation level was within the weights of the staffs and positioned so that all the staffs could be observed during the loading test. Prior to the main loading test, plate load test of 30 and 60 cm diameter steel plates were tested with hydraulic jack reacting against the two outer beams. Settlement of the plates was measured from the independently supported beam by use of Benkelman beams. The main loading test was carried out over a period of 15 days, using 35 incremental loading, from 0 to 1000 kPa, with each load maintained for 4 hr. The study derived parameters that adjusted the predictions to be in reasonable agreement with the calculated and observed results.

Dev and Babbar (2007) carried out six plate load tests on clayey gravel soils at three locations along a canal to determine safe bearing capacity of soil for design of cross drainage along the Bansagar feeder channel of Bansagar canal project. Square plate of 1000 mm x 1000 mm and hydraulic jack was use to perform the test. A gunny bags was filled with sand and stacked to give a load of about 210 to 245 ton to provide sufficient reaction load for the test. The plate was subjected to incremental loadings of 10 T/m$^2$ each by the hydraulic jack, and dial gauge readings was recoded at 0, 4, 10, 20, 30, 40 and 60 min after loading. The load increment continued until settlement of 50 mm or failure of the soil was observed. The safe bearing capacity was found to be 2.80 and 3.38 kg/cm$^2$ at chainage 22.800 km, 2.40 and 3.64 kg/cm$^2$ at chainage 16.803 km. At chainage 15.400 km, settlement was observed to be low, indicating presence of hard stratum.

Teme and Eton (2006) uses a modified plate load tester to determine the bearing capacity of soil in Niger Delta of Nigeria. Due to unfavourable terrain of the area, which does not warrant easy transportation of conventional plate load test equipment, such as heavy reaction metal beams and other dead weight loads to the project sites, a modified plate load test equipment was constructed consisting of a 0.4064 m square base, 0.2032 m diameter and 0.76m long cylindrical steel stem of 15.0mm thickness with load receptacle at the top. Two dial gauges for measurements of settlements and two magnetic dial gauge holders, attached to the stem of two (2) 1.202 m long 9.051m diameter steel rods, driven into 0.75m to the ground for stability and support of dial gauges. Sixteen (16) equal weight 160.0kg, each measuring 62cm x 62cm x5cm were used. The plate load equipment was placed 0.3048m below the ground level at the centre of a 1.22m x 1.22m excavation. The loads were placed one after the other on top of the plate load tester and measurement taken after each load placement at time interval. At the end of the test, it was observed that the allowable bearing capacity was less than the required net bearing capacity. The limitation of the test is that there was no enough time for settlement to be completed before the subsequent increment of load.

Oh and Vanapalli (2012) carried out a modelling analysis on Footing Load Test (FLT) to determine settlement behaviours of in-situ shallow foundations in unsaturated sand. In their studies, five (5) sets of in-situ footing load test were conducted on unsaturated sand using four (4) different sizes of square footing (1, 1.5, 2.5 and 3m), on site that was predominately sand over lain hard clay layer with ground water table of 4.9m. Results for the four different sizes of footings showed that the scale effect is distinctive when the results are plotted using load-settlement relationship. They however, stated that this can be significantly reduced by re-plotting the results as stress verses settlement/width of footing curves. They stated that this is valid when the soil at the site is homogenous and isotropic in nature.

Al-Obaidi *et al.* (2017) carried out a plate load tests on two sites, West Qurna and Faw sites, in Basra Governorate, Iraq, using a circular steel bearing plates of not less than 25 mm thickness, 200 mm$^2$ in area and 504 mm in diameter. The used three dial gauges, for measuring settlement and a hydraulic Jack with Pressure Gauge having a sufficient capacity to provide a maximum vertical load of 300 kN. They drilled three boreholes to a depth of 3 – 4m for each site. Several tests were conducted on the undisturbed soil samples such as classification, compaction and consolidation tests. The plate load tests were carried out at depth of 0.5m from natural ground level and at dry condition. The width of the test pits were at least four times the width of the bearing plate used. The bearing plate was placed on the soil at the bottom of the pit, and an incremental load was applied. On application of each load, enough time was allowed for settlement to occur. The physical property and consolidation test shows that the two soil samples were medium silty clay with high compressibility. The test was quite useful for estimating the bearing capacity of subgrade and sub-base layers and was used to solve the design problems of rigid pavement.

Load impression test using 10kg load, dropping through a height of 1m with a cross sectional area of 207.98cm$^2$ at the foundation depth of 1.25cm on silty clay soil was carried out to predict bearing capacity of shallow foundation using in-situ and conventional experimental methods by John and Thomas (2017). From their findings the average bearing capacity obtained was higher than the conventional methods.

A Comparative study on four different in-situ tests (Standard Penetration Test - SPT, Cone Penetration Test – CPT, Dilatometer Test - DMT and Pressuremeter Test - PMT) for site investigation was conducted by Sahadat *et al*. (2005) to compare the bearing capacity and settlement values, predicted from in-situ tests with those observed from plate load test. The SPT -N values were obtained using a standard 50.8mm O.D., 34.9 mm I.D. Sampling spoon driven with a 63.5 kg hammer, falling from a height of 762 mm. In-situ cone penetrometer testing was performed at seven boring locations to aid in evaluating soil bearing capacity and settlement characteristics. The soil characteristics, interpreted from the CPT data were similar to that observed from the SPT data in some borings. However, interpretation of CPT data indicated thin clay seams in between the sandy silt layer. Since the SPT was performed only in layers of 457 mm increments, these thin seams may have been missed. A total of seven in-situ pressuremeter tests were performed on the site. The Pressure Limit (PL), determined using the correlations from the PMT data is pressure at which failure occurs and Pressuremeter Modulus (EM), estimated from the test is a representation of stiffness of the soil. The PMT produces more direct measurements of soil compressibility and lateral stresses than the SPT and CPT. Seven dilatometer tests were performed to evaluate the soil bearing capacity and settlement characteristics. The soil resistance measured during insertion of dilatometer blade was correlated with strength of the granular soils, while the soil modulus, undrained strength and other parameters are determined during dilation of the blade against the soil. The strength parameters from the DMT test results were computed using Schmertmann method and the results. A plate load test was performed using a 2.5 × 2.5cm square plate. Subsoil encountered around this vicinity was considered to be the least favourable for direct support of the footings loads of (96 kPa. At the end of the tests, the bearing capacity and settlement predicted by the four in-situ methods were compared with the observed settlement from the plate load test. SPT and CPT overestimated the settlement, while DMT and PMT predicted settlements less than those observed in the field by the plate load test.

Costa *et al.* (2003) conducted ten plate load tests using a rigid circular steel bearing plate, placed on the ground at a depth of 1.5 m. The plate was 0.8 m in diameter and 25 mm thickness. Two loading procedures were used: Slow Maintained Load (SML) and Quick Maintained Load (QML). The tests were conducted in two distinct series. In the first series, five tests were carried out after inundating the pit for a period of 24hr prior to beginning of the test (inundated tests). In the second series, the tests were performed preserving in-situ water content of the soil (moist tests). A new test pit was excavated for each test. All tests were carried out following Brazilian Standards for Load Tests on Shallow Foundations (NBR 6489-84) and for Static Loading Tests (MB 3472-91), which are consistent with ASTM Standard Test Method for Bearing Capacity of Soils for Static Load and Spread Footings (D 1194-72). In the SML tests, settlements after each load increment were considered stabilized for period of 24hr. Also, in the QML tests, each load increment was held constant for a period of 15 min and settlement readings were taken at 0, 1, 2, 3, 6, 9, 12, and 15 min. Soil matric suction was monitored during the tests using tensiometers, installed at the bottom of the test pit. Analysis of the results showed that response of the soil-plate systems were highly influenced by magnitude of soil matric suction in lateritic soils. A small increase in suction from 0 to 10 kPa led to an increase of approximately 100% in the failure stress.

Avesani-Neto (2019) performed static and cyclic plate load test on three test sections, directly on subgrade, on unreinforced granular sub-base (GSB) layer, and on granular sub-base layer, reinforced with a High Density Polyethylene (HDPE), geo-cell with rough and perforated walls, tensile strength of 14N/mm, height cell (h) of 150mm and pocket size (diameter of the cell, d) of 192mm – aspect ratio, h/d equal to 0.78. A circular plate load with a 300-mm diameter was selected to simulate the diameter of the vehicle tire pressure. Two dial gauges were placed on the circular plate and two dial gauges were used to monitor the full surface movements. At the end, the two-layer system theory can be employed simply and efficiently to reinterpret plate load test results and to determine the relationship between the geocell-reinforced and subgrade layers moduli.

Teodoru and Toma (2009) carried out a numerical analysis of plate load test to determine size effect and magnitude of loading on settlement of soil. The study was based on comparison between results, obtained by Finite Element Method (FEM) using Mohr-Coulomb soil model and by some observations from literature. The obtained numerical results from the plate load test revealed that subgrade reaction coefficient, Young Modulus is strictly depended on parameters like size of the loaded area and loading magnitude, which are completely not material properties of soil as against the conventional methods of determining these properties.

Guil and Ceylanoglu (2016) carried out study to evaluate bearing capacity using estimated methods, based on plate load tests. In their study, bearing capacities of rock units were determined using plate load test and estimated method based on various empirical methods from the literature. At the end of their study, estimated bearing capacity values greatly differed from others with respect to in-situ determined bearing capacity values in most of the equations. For example, bearing capacity value of magnetite, obtained as a result of plate loading test was 110.49 kg/cm², while the closest value to this during calculations was that of El-Naqa equation that gave 91.08 kg/cm$^2$.

Pentelidis (2005) conducted a study to determine the characteristics performance of plate bearing test on soil strength test. In his study, plate bearing test was used to give a clear distinction between Modulus of Elasticity $E_{Young}$ and Modulus of Elastic Deformation $E_{Def}$, which is commonly used in highway earth-works. Moreover, soil classification diagram was given, in which the soils were classified by their shear strength parameters and behavior, as totally elastic or elastoplastic, under specific loading, applied by rigid circular plate. The plate diameter ranged from 300 to 700mm and incremental loading was from 200, 250, 300, 350, 400, 450 and 500kN/m$^2$ at time intervals. A good estimation of the Modulus of Elasticity was achieved using correlation equation with the data derived from the test (load-settlement curve).

Ping *et al*. (1997) carried out field investigation to evaluate pavement layer moduli using field plate bearing load test. The test was carried out using water tanker of weight of 27240kg and a hydraulic jack with a spherical bearing attachment, capable of applying load increments, a dial gauge and circular steel plate of 3.66m diameter. The test was conducted on 20 flexible pavement sites across Florida, USA. At each site, bearing characteristics of the base, subgrade and embankment layers were determined. The results of the investigation showed that plate bearing test was considered to be best in determining base, subgrade and embankment materials in Florida using Burmister two-layer theory to back calculate the modulus of elasticity of each layer. The validity of this test was warranted by ELSYM 5 program. The limitation of the study is that the hydraulic jack used cannot sustain load for long period of time, hence getting the actual total settlement was not possible.

Ghavami *et al*. (2019) uses Macintosh probe test and Special Analysis of Surface Wave (SASW) as non-destructive test methods to predict allowable bearing capacity of shallow foundation. They made use of laboratory method to characterize the soil, whose water was located at 10m below the ground surface. The Macintosh probe test was performed at four locations at to estimate bearing capacity of the soil. Also, SASW method was conducted in four lines to determine shear wave velocity at 0.5, 1, 2, and 3 m depths on each segment. The spacing between the first receiver and source was kept equal to the spacing between the two receivers. The testing arrangement includes hammer, two receivers and data acquisition system. At the end of the study, allowable bearing capacity of shallow foundation was estimated based on shear wave velocity by using empirical and theoretical methods. The accuracy of the methods depends on the quality control of the field SASW measured.

An experimental investigation on load carrying capacity of micropile in soft clay was investigated by Borthakur and Dey (2017), to determine load-settlement behaviours on two different sets of micropiles groups with 25 and 50 mm diameters. In their study, micropiles were constructed in dug test pit in very soft consistency. The test pit was of size 2 m (width) x 4 m (length) x 3 m (depth). Variables that were taken into consideration for the study were diameter, length and spacing of the micropiles in groups. Micropiles of two different diameters (d) 50 mm and 25 mm and three different lengths of 24d, 32d and 40d were constructed. The micropiles were arranged in three different spacing 3d, 4.5d and 6d. For the 50 mm diameter micropiles, the pile caps were constructed in two methods namely; one resting on the ground surface and one above. Also, for the 25 mm diameter micropile, the pile was constructed above the ground surface. In carrying out the experiment, a load truss was erected along the center line of the micropile cap and vertical incremental loadings were applied using hydraulic jack. 50kN cell was used to measure the applied load and two dial gauges of sensitivity 0.01mm and LVDT were placed at diametrical and opposite ends of the micropiles respectively. This was to measure the settlement manually. Also, the plate load test was performed with three different plate sizes of 300 mm x 300 mm, 600 mm x 600 mm and 750 mm x 750 mm to determine the in-situ bearing capacity of the soft clay. Effect of diameter, length and spacing of 25 and 50 mm, both increased with increase in diameter, length and spacing.

Anderson *et al.* (2017) carried out an investigation to examine settlement prediction for in-situ load test using the conventional method (Standard Penetration Test, SPT, Cone Penetration Test, CPT, Pressure Meter Test, PMT, and Flat Dilatometer Test, DMT) and Finite Element method analysis. In the study, 1.8 m diameter, 0.6 m thick concrete circular footing was embedded into 0.6m ground, with groundwater table was at 1.7m. The footing was statically loaded successively with reaction weights from 0 to 222kN/m$^2$. The load deformation response was monitored using three load cells at 120° and four Linear Variation Displacement Transformer (LVDTs), at 90°, connected to a data acquisition system. Prediction of the footing settlement was made by conventional as well as finite element methods. Results of the investigation showed that static load settlement was over predicted by all the methods, while finite element method analysis using either parameter provided poor settlement predictions.

## 3.0 LABORATORY PLATE LOAD TEST

Numerous studies have also been carried in laboratory using models and large scale foundations to determine the load-settlement relationship of foundations. A laboratory model test on a box measuring 1 m length by 304.4 mm width and 914 mm depth was conducted by Omar *et al*, (1993) to determine the ultimate bearing capacity of a strip and square foundation, supported by sand with geogrid reinforcement. The model foundation was placed on the surface of the sand bed and load applied to the model foundation through hydraulic jack. The load and corresponding settlement was measured using dial gauge and proving ring. The result shows that the findings cannot be directly transported to full-size foundations without additional verification.

Gul and Ceylanoglu (2013) carried out plate load test in laboratory and field to determine bearing capacity of different rock units which was found to be easy, quick and cheap. In the laboratory method, accessories such as batteries, data logger, power inverter, hydraulic pump with pressure transducer for application of pressure, steel discs, displacement transducer, ground plate, hammer and spatula for ground preparation, were used to obtain bearing capacity of six materials (magnetite, syenite, serpentinc, limestone, clayey limestone and gypsum). The materials were chosen as they occur at three different open pits. The plate loading tests were undertaken at 2m interval a cross a vertical line, parallel to the bench face at the same location using a loaded truck as static load, hydraulic pump, a plate and data logger to determine bearing capacity. A total of 96 plate loading tests were carried out. At the end, laboratory and field tests results were compared with seismic velocity data with good results found for magnetite, syenite, serpentinc, limestone, clayey limestone, excepted for gypsum and dump soils. Base on the field and laboratory results, bearing capacity the rock units was determined and four bearing capacity classes were proposed.

Shirvani and Shooshpasha (2015) performed laboratory plate load test on cement stabilised footing on sandy soil in a chamber that was cubical with dimension of 130 cm x 130 cm x 100 cm using hydraulic jack with appropriate capacity to maintain the maximum predicted load. The concrete footings were of various sizes (10 cm x 10 cm x 10 cm, 20 cm x 20 cm x 10 cm and 30 cm x 30 cm x 10 cm). A pressure gauge of capacity 10, 60, and 160bar for taking measurement and three dial gauges were used. It was observed that increasing cement content and dimension of the stabilised region, increases the bearing capacity of the soil. Also, each of these samples showed the same behaviour, with maximum load and corresponding settlement being nearly identical.

An attempt was also made by Vitale and Skuodis (2013) in carrying out analysis of shallow foundation settlement using different calculation methods in predicting deformation of soils. Finite Element (FE) approach was suggested for evaluating correctly the total settlement compared to other methods of analysis.

McMahon *et al.* (2013) carried out a model test using energy method to determine the load-settlement behaviours of a circular shallow foundation based on kinematic deformation mechanism for cavity expansion of clay soils. An upper bound on the bearing capacity of shallow foundation was found by equating the work done in moving the foundation to the energy stored or dissipated within the soil using an assumed mechanism. At the end they used elastic and plastic work done within the soil and equate it to the footing work, with yield being defined using ‘Von-Mises criterion.

Mohanty and Kumar (2018) conducted a study using multi-objectives optimization technique, where a Non-Dominated Sorting Genetic Algorithm (NSGA

II) was combined with learning algorithm (neural network) to develop a prediction model based on SPT data based on the Peteto optimal front. Based on different statistical parameters used in the analysis, the proposed method was found to be more efficient compared to other existing methods of analysis.

Khosrojerdi *et al*. (2019) developed a prediction equation for estimating the settlement of footings placed on reinforced soil. In their studies, they used footing geometry (width and length), soil friction angle and cohesion, reinforcement characteristics (stiffness, spacing, length, and number of reinforcement layers), and applied static loads from 50 to 600 kPa. The results of the parametric study were used to conduct a regression analysis. Evaluation of the developed prediction equation showed that the proposed equation can be used with fair accuracy in estimating the maximum settlement of foundations placed on reinforced soil under service loads. The sensitivity analysis of the prediction equation of settlement of reinforced soil foundation indicated that the soil friction angle had the highest effect on reinforced soil foundation settlement in the prediction model. They stated that the developed prediction equation can contribute to better understanding of the behaviours of reinforced soil foundation and be easily used by practitioners for preliminary designs of reinforced soil foundation.

Alawaji (1997) conducted a research on model plate load test on collapsible soil from Al Helwah province of Saudi Arabia. He used both oedometer and plate load test models with wetting periods, plate size, over burden pressure, stage loading durations and soil thickness to evaluate the collapse nature of the soil. Load was applied in cumulative increments such that the net pressure follows. In general, the loads increments were 0, 13, 25, 50, 100, 50, 25, 50, 100, 200, 300kPa, etc. The loading increment for dry soil was kept after 15min and 2hr for wet soil. After each load increment, the cumulative load was maintained until all settlements and collapse had ceased, when the rate of deformation reaches less than or equal to 0.001 mm/min over the last 10 to 15 minutes. Cylindrical steel container of 45cm diameter with wall thickness of 1cm and 35cm height with two dial gauges and two drainage paths were used. While the laboratory test used single and double oedometer tests with 50 and 70mm diameter respectively, and 50cm thickness. At the end, the soil was found to have a relatively high collapsible potential of 12% under 200 kPa over burden pressure, and collapse prediction, based on oedometer test underestimated the measured plate collapse settlement.

Alhaji and Alhassan (2017) conducted a model test on bamboo reinforcement A-7-6 clay soil to determine load-settlement. In their research, they first carried out load-settlement test on unreinforced compacted soil bases at predetermined moisture content. In the second test, a similar compaction energy level and same predetermine moisture content was used but with one reinforcement layer placed after the fifth layer compaction. The test, with one bamboo reinforcement layer each was placed after fourth and fifth compaction layers. The process was continued down to the fifth reinforcement layer. The model of the base clay soil was compacted in the mould at predetermined maximum dry density and optimum moisture content with inclusion of the bamboo reinforcements. Footing plate of 38mm diameter was used to transfer the load to the compacted soil. At the end of the test, ultimate bearing capacity of the reinforced clay soil was observed to increase at first from 0 to 435kN/m$^2$ and to 600kN/m$^2$ at first and second layers respectively, after which it decrease to 495kN/m$^2$ at the 5 layer. This gave the ultimate bamboo layers required for effective reinforcement of the clay soil.

Risk analysis was used by Dasaka (2012) as design tool to determine various sources of uncertainties on performance of plate load test on field and laboratory model plate load tests. The plate load tests were carried out with plate of size 0.6 m x 0.6 m, and the test was conducted at 4 m depth below the natural ground level. Ground water table was not observed in the vicinity of the plate. The load was applied on the plate through hydraulic jack in 5 equal increments of 100 kPa. It was noted during every loading stage, that there was a drop in the pressure on the plate, as the plate settles into the soil. A pressure of 400 kPa was initially applied on the plate, with the corresponding pressure gauge reading of 320 kg/cm$^2$. However, due to the fact that the hydraulic jack was not able to hold the applied pressure constant, a reduced pressure gauge reading of 250 kg/cm$^2$ was noticed after almost 12 hours from the application of 4th load increment, which correspond to a pressure of 312.5 kPa. For laboratory model test, it was carried out on clay bed in a test tank of dimensions 46 cm x 46 cm and 41 cm in depth. The moist soil in the tank was compacted in layers and for each layer 9 kg of soil having 30% water content was used. A plate of size 10 cm x 10 cm x 0.7 cm was kept at the center of the tank and load was applied by keeping appropriate load on the lever arm to get the desired load on the plate. The load was maintained during each loading stage for duration of 1 hour. Plate load test, which is referred as most reliable in-situ testing technique to obtain load settlement response, may give rise to unrealistic results if not properly conducted. The study focuses on the analysis of laboratory plate load test results, to understand the effect of maintained and non-maintained load during each loading stage.

## 4.0 SEMI -LABORATORY PLATE LOAD TEST

Studies using semi-laboratory plate load test approach have also been carried out. Mohite and Admane (2015) design a modified plate load test similar to the conventional one were undisturbed soil sample can be tested. In the study, undisturbed soil sample was placed on the base plate and load was applied using reaction frame method. The reaction frame was design for loading of about 300, 150 and 50kN using lever arm arrangement. This approach is similar to California Bearing Ratio (CBR) test procedure. The study gives accurate results when compared with the standard plate load test. Its limitation is that, obtaining undisturbed samples could lead to serious error in the entire procedure.

Verma *et al*. (2013) investigated bearing capacity and settlement of foundation resting on a granular layered soil using model test apparatus with square plates of various sizes (250, 300, and 400mm) and thickness of 25mm, and presented results that showed ultimate bearing capacity of layered soil, being more than that of homogeneous soil bed, for a particular plate size. The result also showed that bearing capacity of soil increase with increase in size of square plate, but decrease in settlement. The limitation of their findings is that it was carried out on model, where the natural properties and pore water pressure of the soil were disturbed.

Effect of particle and plate sizes was on bearing capacity and settlement was investigated by Halai *et al.* (2012) with the aim of seeing the possibility of using of smaller plate sizes on site, which will be more economical for plate testing. An assemble of a model test apparatus was set up in laboratory with the aid of reference reaction beam and a hydraulic jack and a test tank with soil of same particle sizes. At the end of the test, there was very little influence of scale effect between soil and foundation. The major limitation is that the test used a model and the samples used were disturbed which will not reflect the situation on site.

Sultana and Dey (2016) conducted settlement tests on clay and sandy soils to determine uncertainty of reaction loading in plate load tests. Some of the tests were conducted on steel tank of size 0.1 m x 0.1 m x 0.1 m, and others in a test pit of size 3.0 m x 2.0 m x 2.7 m deep. Load was applied through a hydraulic jack, attached to a loading frame and the reaction force was measured by an electronic load cell. Settlement was measured through two LVDTs, placed at opposite ends of the test plate. A total of six tests (two gravity loading and four reaction loading) with loadings ranging from 0.24 to 11.19 kN were carried out and 46 number of loading data were collected for reaction loading. At the end of their study, it was conclude that one more uncertainty, due to load increment for a reaction type loading in a plate load test exist, compared to gravity loading. Also, the COV of the load increment in the reaction loading was found to be within a range of 0.006 to 0.066, with a mean value of 0.018.

Two square steel plates with roughened bases, having sizes 0.l5m x 0.l5m and 0.30m x 0.30m and thickness of 20mm each, were used by Saran *et al*. (1995) in settlement test. The loading arrangement consisted of a compensating lever arm mechanism along with a hydraulic jack. Vertical displacements of the footings were measured by fixing four dial gauges, one at each corner of the plate. Two containers of sizes, appropriate to the tank were used to deposit the sand by rainfall technique, in lift of 100mm each. The test was carried out on unreinforced and reinforced sand beds at 70% relative density. The reinforced base contains 2, 3, 4, 6 and 8 geogrid layers of sizes varying from lB to 5B (B, being the size of the square plate). At the end of the test, it was observed that under repeated loading conditions, there was a decrease in total settlement and improvement in the bearing capacity, upon reinforcing the sand bed. With larger sizes and number of reinforcements, larger decrease in total settlements and greater enhancements in bearing capacity values are observed.

Semi-model load tests were conducted by Kesharwani *et al.* (2015), in a rectangular tank, having internal sizes as 1.50 m x 1.5m x 0.75m. The test plate was a mild steel having thickness of 25.4 mm. The tank size was selected considering sizes of the test plates, such that the size of the test tank would be at least five times the size of the largest test plate. Three sizes (100, 150 and 200 mm) of model test footing were used. The load was applied through a manually operated hydraulic jack of 500kN capacity, supported by load reaction truss. The applied load was recorded using pressure gauge, mounted on the hydraulic jack. Settlement of the footings was observed using dial gauges mounted against reference beams. Results of their study indicated decrease in settlement with the increase in coarse aggregate percentages. Bearing pressure decreases with increase in size of footing.

Mogre and Raut (2013) performed plate load test on fully saturated cohesive soil using 30 cm x 30 cm x 2 cm bearing plate, placed on piston of hydraulic jack. At the commencement of the test, load of 70g/cm$^2$ was preloaded and release to account for overburden pressure of the soil and to cause initial settlement. Water level was maintained by constant pumping from the sites. At each load increment, dial gauge reading was taken after 1, 4, 10, 20, 40 and 60min, until the settlement was steady at 0.02 mm/hr before the next incremental loading. This continued up to the final loading of 7 tons. The result indicated ultimate bearing capacity of the soil at the site to be 58tons/m$^2$. It was therefore, suggested that, for safe conduct of plate load test on soft and fully saturated clay, underlain by cohesive soils, excavation of test pit should be done in steps to avoid sliding or collapsing, and sump pump should be provided in the pit to dewatering away from the plate.

Kumar and Bhoi (2009) investigated effect of interference of two strip footings, without having any provision of tilt, resting on surface of dry sand was investigated using series of small scale model tests. In the investigation, a rectangular steel tank of size 2.0 m length x 0.37 m width x 0.65 m depth was used. The tests were conducted using steel footing of size 7.0 cm width x 36.0 cm length x 2.5 cm thickness. At the end of the test, it was noted that bearing capacity of footing is maximum at a certain critical spacing. The interference effect was even more extensive for higher relative densities.

A simplified estimation method for predicting final consolidation settlement of floating soil cement column composite stabilization technique, below an embankment has been proposed by Ishikura *et al*. (2016). A model of rigid cell wall of 250 x 100 mm area, and 400 mm depth was used. The panels of the container were made from transparent perspex which allowed observation of deformation of soil on the front face during loading/consolidation. The model arrangement allowed drainage from both upper plates via a clearance gap of 2.5 mm around the outer edge of the upper loading plate and the bottom of the cell, via layer of porous plastic. It uses a simple stress distribution ratio, based on magnitude of shear stress at the column-soil interface. The advantage of this method is that it allows determination of the consolidating layer thickness as a function of simply derived parameters such as the degree of improvement, loading conditions and undrained soil strength.

Ornek *et al.* (2012) used data from field to run Artificial Neutral Networks (ANNs) and Multi-Linear Regression Model (MLR) to predict bearing capacity of circular shallow footings, supported by layers of compacted granular fill over clay soil. At the field, series I of the tests was conducted using seven different footing diameters of 0.06, 0.09, 0.12, 0.30, 0.45, 0.60 and 0.90m on the surface of natural clay soil deposit. Series II was same as series I except that it was placed on the granular fill layers, settled on the natural clay deposit. The main objectives of these large-scale tests was to model the full-scale behaviours of reinforced soil footings more accurately, to evaluate the performance of granular fill layers stabilizing the natural clay soil with respect to the bearing capacity and to examine effects of the thickness of granular fill layers. The natural clay showed increase in bearing capacity with increase in foundation size, which generally resembled a typical punching shear failure. The granular fill under natural clay has considerable effort on bearing capacity and settlement characteristics. However, ANN model shows a better performance than MLR in both training and the testing phases.

Bensallem *et al.* (2014) developed a time-dependent prediction model to determine settlement amplitude behaviours of clay soil during dry process. In the study, they use laboratory and full-scale in-situ model tests to predict settlement of the clay soil. The in-situ test was performed after removal of non-expansive top layer. The experimental device consisted of four rigid foundations (of one square meter each) was placed over the clay layer. A loading reaction beam was placed over each foundation independently and load was applied with a hydraulic jack with an area of 380cm$^2$. Each foundation was used at a certain moment of the experiment, relative to a specific moisture state. For moisture stage, water supply network was placed over the entire tested area to measure different moisture content at each stage. During the experiment process, each hydraulic state was accompanied by specific ground settlement. Laboratory test performed to determine $\emptyset$ and c on the clay samples. The predicted analytical and laboratory settlement amplitude values correspond practically to the in-situ model soil behaviours.

Sultana and Dey (2018) uses both gravity loadings and reaction truss loading methods of plate load test to estimate ultimate bearing capacity of footings on soft clay soil on site. Eighteen PLTs were performed, both in tank in the laboratory and on site in a test pit. Two tests were performed using gravity loading, while the rest were performed using reaction loading. Four different sizes of square plates (0.1, 0.2, 0.3 and 0.45 m width) and two different sizes of circular plates (0.1 and 0.2 m diameter) with the plate thickness (0.018 and 0.025m) were used. On each plate, three tests were performed at different soil consistencies. At the end of the study, bearing pressure against settlement curves show a high degree of variability with shape and size of plate in soft clayey soil. Also, a reaction truss loadings was found to have co-efficient of variance of 0.018 and was assumed to have a normally distributed random variable compared to that of gravity loading method. The sensitivity analysis, by Cosine Amplitude Method (CAM) showed that the bearing pressure was highly influenced by settlement and unconfined compressive strength, and less influenced by width and area of test plate.

In an attempt to improve bearing capacity of soil using natural geotextile, Panigrahi and Pradhan (2019) conducted model laboratory study on square footings, supported on reinforced sand beds, using a brick masonry tank of size 0.65 m × 0.65 m × 0.3 m, constructed in laboratory. The model square footing of size 50 mm × 50 mm or 75 mm × 75 mm was placed at the center on the test bed and the fabricated loading frame was placed centrally on the footing. Dial gauges were fitted at the bottom surface of the loading platform to record settlement. A total of 32 loading tests, ranging from 5 to 100 kPa were conducted to evaluate effects of single layer reinforcement of the base soil. The testing programme considered three parameters: depth of reinforcement, area of reinforcement and footing size. The results indicated that the maximum gain in bearing capacity of footings on geotextile reinforced soil increased by a factor of 3.37 as compared to unreinforced soil.

Dasaka *et al.* (2013) conducted laboratory and field plate load tests in other to determine effect of maintaining and non-maintaining loading on the bearing plates, on the load–settlement response. In the study, the authors made use of reaction loading beam with hand operated hydraulic jack, teat plate of size 0.6m by 0.6m and 25mm thick, pressure gauge and dial gauges for measuring load and deformations respectively. Load increment from 100 to 500 kPa was used. The test was conducted in 4m depth test pit. At the end of their study, they observed that for maintained loading, settlements increase slowly and finally reduce to a rate less than 0.02 mm/min, whereas, for non-maintained loading case, after a high initial settlement, a rebound was observed, which gradually increased with time and finally attained a near constant value. However, it was observed that the bearing resistance of the soil was highly overestimated in non-maintained load as compared to the maintained load case.

## 5.0 CONCLUSIONS

It is a common knowledge that there is difficulty in correctly predicting bearing capacity and settlement of foundations due to inconveniences in sampling operations. Therefore, the testing of the mechanical properties of soil under field conditions is most authentic, because of the absence of distortions, which are connected with collection of samples and their transportation.

This review study considered load-settlement mechanisms, used to investigate footings at laboratory, semi-laboratory and field levels.

It was observed that the loading mechanisms differ from direct load to indirect load application through lever arm to jack/reaction frames.

Application of loading through jack was observed to be the most common, but and can only apply and keep constant loading for short period of time. This will not allowed enough time for consolidation settlement in case of soil bases of clayey nature.

Field load bearing tests still stand as the most reliable method of estimating bearing capacity and settlement for shallow foundations.

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