Responsible Design and Delivery of the Constructed Project
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RAPID LOAD TESTING OF STONE COLUMNS TO AID DESIGN OF FOUNDATIONS ON IMPROVED GROUND

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Building Codes and best practice require load testing of embedded structural foundation elements to validate design and construction execution quality. This requirement is particularly challenging when associated with ground improvement schemes relying on granular reinforcing/stone columns. Stone columns present an economic solution for improving the bearing capacity of shallow foundations on soft soils. A novel impulse load test was developed and used to quantify the load-displacement response of shallow foundations supported on stone columns at a clay site. The device is referred to as the Rapid Plate Load Tester (RPLT) and is a modified version of the Axial Compressive Force Pulse test for deep foundations. In this paper, the comprehensive site investigation, stone columns construction, load testing procedure, and data analysis are described. Static and dynamic field tests were performed to target loads of 2000 kN and equivalent bearing pressures of 500kPa. The results obtained from the RPLT tests were used to derive equivalent static load settlement curves for footings on both the natural clay ground and improved ground and compared with the results obtained from the full-scale static load tests.

Keywords: Raft, Clay, Unloading point method, Shallow foundations, Static load test.

1 INTRODUCTION

Economic activity has been on a consistent upward trajectory in the Gulf Cooperation Council (GCC) states since 2004. The region has witnessed the construction of numerous new airports, large industrial zones with downstream processing plants, and waterfront reclamation for both low and high rise residential projects. Many of these large projects were undertaken in marginal coastal areas with poor ground conditions unsuitable for sustaining high structural loads without large associated settlements. Large scale ground improvement schemes have repeatedly proven to be a cost effective alternative to pile foundations for structures with working bearing pressures on the order of 200 kPa such as pipe racks, warehouses, and low-rise buildings. Ground improvement is typically executed by specialist contractors on a design build contract basis. Such contractors will base their design on a combination of recommendations available in the literature and their observations on the performance of past designs in local geologies. Acceptance criteria are generally specified in terms of a full scale static load test on a representative foundation, such as a two meter wide square footing, using a test method such as the American Standard for Testing & Materials (ASTM) D1194 (1994) for the Plate Load Test (PLT).

The high cost, technical and logistical complexity, and market availability of suppliers providing full scale load testing has led engineers to alternative test methods. Touma *et al.* (2016) described the development of the Rapid Plate Load Test (RPLT), a device to perform rapid load tests on footings, inspired by similar tests on piles as described in ASTM D7383 (2010). A schematic of the proposed RPLT is presented in Figure 1. The primary components are the steel footing, instrumentation anvil, guide frame, and an eight ton falling weight. The secondary components consist of acquisition devices and electronic instrumentation. The instrumentation consists of a photocell, reference laser, load cell, and accelerometers. The simplified procedure consisted of raising the falling weight within the confines of the guide frame to a designated height of up to 2m. The load pulse generated by the falling weight striking the anvil is measured by a load cell embedded within the anvil, and the vertical displacement of the steel footing is measured by a photocell and an accelerometer. Two additional accelerometers are fastened to the footing to jointly acquire acceleration and velocity. The acquired signals from the instrumentation are used to generate time history plots, from which a relationship between applied load and vertical settlement can be determined. A research program undertook several RPLT tests at a clay site in Lebanon. One of the outcomes of the research program was a comparison of load settlement curves obtained by static load test and RPLT.

The objective of this paper is to investigate the RPLT performance on ground improved with stone columns. For this purpose, stone column groups with different configurations were installed in the same test zone in which the tests reported in Touma *et al.* (2016) were conducted. One static load test and three dynamic RPLT tests were conducted using a steel grillage footing that was supported on clay reinforced with stone columns in three configurations providing an area replacement ratio ranging between 16.5 and 29%. In addition, a comprehensive field and laboratory investigation campaign that consisted of standard penetration tests (SPT, ASTM D1586-11), pressuremeter tests (PMT, ASTM D4719-07), and CU triaxial tests with pore pressure measurement was performed (ASTM D4767-11) to characterize the soil profile at the site. The results of the site investigation in addition to the results of the static and RPLT tests are presented in this paper.

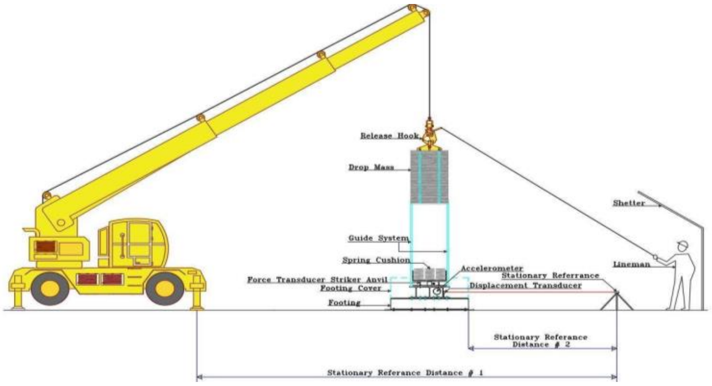


Figure 1. Schematic of the RPLT test device.

2 SITE INVESTIGATION

The investigation consisted of two boreholes and three test pits in the immediate vicinity of the test footing locations. The first borehole was used to conduct SPT tests and the second borehole was used to conduct pressure meter tests. Both boreholes were also used to retrieve undisturbed samples using thin-walled Shelby tubes. Data from two additional boreholes was also available in the site from previous testing. Test pits were excavated up to a depth of 3 m below NSL with the aid of an excavator so as to visually inspect the ground conditions up to a shallow depth. The sampling, preservation and transportation of the samples were carried out as per ASTM D4220-14. The disturbed overburden samples and the relatively undisturbed soil samples that were collected from the boreholes were labeled and preserved properly before transportation to the laboratory for testing. Undisturbed specimens were used as a basis for determining the shear strength parameters of the soil using triaxial testing. Field borehole logs were developed on the basis of the material encountered at the site, which was then confirmed with laboratory test results.

Groundwater was encountered at a depth of 2.5m below NGL at the time of the investigation. The investigation revealed generally uniform soil conditions across the site. Density and consistency were assessed using SPT tests and Atterberg limits and used in conjunction with the boring logs to determine the generalized soil profile. The top overburden soil comprises sandy Lean Clay/Fat Clay up to a depth of 7.5 m below the NSL. The top layer is underlain by Clayey Gravel with sand present up to a depth of 18 m below NSL. Below the gravel layer, a sandy Lean Clay layer is present up to the maximum investigated depth of 22 m below NSL. The results of the pressuremeter tests that were conducted at depths of 2.5m, 5.75m, and 7.75m are presented in Figure 2a. The pressuremeter results suggest an undrained shear strength ranging between 100 and 130 kPa, with an associated pressuremeter modulus ranging between 8 to 12 MPa. Similarly, sample results from CU triaxial tests that were conducted on specimens obtained from a depth of 3.0 to 3.8m are presented in Figure 2b. Other triaxial tests were conducted on specimens obtained from depths ranging from 1.5m to 5.0m, but their results are not shown for length limitations. The results of the triaxial tests indicated a response that is typical of a slightly overconsolidated to overconsolidated clay, with most of the tested specimens showing a strain-hardening behavior at large strains. This behavior was associated with the generation of negative pore water pressure as a result of the dilative tendency at larger strains. Positive pore water pressures were initially recorded at very small strains and were followed by a tendency for dilation. This dilative tendency was stronger in specimens obtained from depths ranging from (3.0 to 5.0m) compared to specimens obtained from shallower depths (1.5m to 3.0m). These results indicate that the clay at shallower depths may be less overconsolidated than the deeper clays which show larger undrained shear strength and stiffness values.

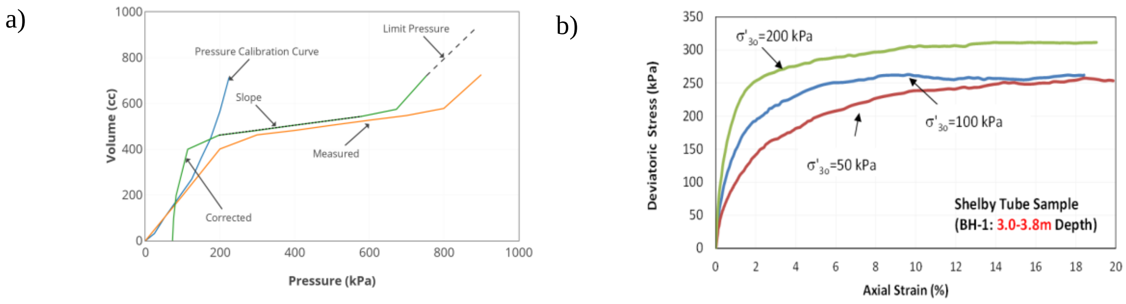


Figure 2. Representative results from a) Pressuremeter and b) CU triaxial test.

3 SITE PREPARATION AND STONE COLUMNS CONSTRUCTION

The research plot boundary was 18m x 18m and consisted of a grid of twelve locations intended for load tests. The site was cleared of vegetation, grubbed, and leveled. Stone columns installation used techniques similar to those used in installing Rammed Stone Columns, as described by Barksdale *et al.* (1983). A percussion drilling rig was used to excavate the 50-cm and 60-cm diameter columns. The excavated bore remained stable. After removal of the drill string, the depth of the excavation bottom was checked. The column was constructed in four to five lifts, each of approximately 0.25 m^3. A hopper with the measured lift volume was used in discharging gravel through a five inch diameter pipe to the bottom of the excavated hole. A fabricated steel mandrel was fastened to the rig chisel and repeated blows were used to compact the lift. Sample configurations are illustrated in Figure 3 showing the the two five column configurations and the three column configuration. The unit cell has been delineated in each configuration and the area replacement ratio is calculated as the ratio of the column area to the unit cell area. The baseline reinforcement ratio of 17.4% was tested by static load test, and using multiple and single cycle rapid load tests at an adjacent location. An over-reinforced location and an under-reinforced location, with area replacement ratios of 28.9% and 16.6%, respectively, were tested with multiple cycle rapid load tests. In total, eighteen stone columns were installed across four locations. The remaining locations within the testing grid were tested in an unreinforced state and were subjected to a selection of multiple and single cycle rapid load tests.

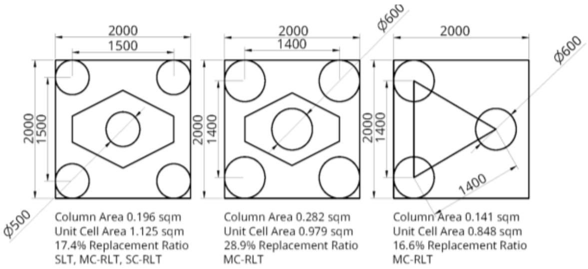


Figure 3. Column configuration at a) Location 2, b) Location 3, and c) Location 9 with dimensions in millimeters.

4 ASSESSMENT OF STATIC RESPONSE

Static load tests were performed on unimproved ground and on the improved footing locations described in Figure 3 in general accordance with ASTM D1194 (1994). A defining characteristic of the RPLT setup is that the grillage foundation and bottom plate can be fastened to either a reaction assembly for a static load test or to a drop hammer for a dynamic test, and the bottom plate in this instance had dimensions of 2m x 2m. Load was increased at a nominal increment of less than 200 kN and displacements were measured at the end of fifteen minute intervals. In the case of the test on stone columns, the footing continued to creep beyond the measurement time interval of fifteen minutes, and after one hour of maintaining the load, the footing was deemed to have failed as shown in Figure 4a. In contrast, the footing on unimproved ground settled beyond the limit of the load jack at approximately 1600 kN. A second cycle was performed which also displayed settlement beyond the fifteen minute measurement interval and the test was hastily terminated.

The load settlement curves for footings supported on unimproved and improved ground are presented in Figure 4b. Ultimate loads of 1610 kN and 1980 kN (pressures of 402.5 kPa and 495 kPa, respectively) were applied to the unimproved and improved footing locations. The curves exhibited an initial linear region that is characterized by a linearly proportional relationship between load and settlement. It is clearly evident that the load test pertaining to a footing on improved ground exhibits an initial stiffness that is improved in comparison to that of the unimproved ground. The linear region is followed by a nonlinear transition region and a final linear region, evidencing behavior described by Akbas and Kulhawy (2009). The tests were terminated due to continuing creep beyond the fifteen minute measurement interval.

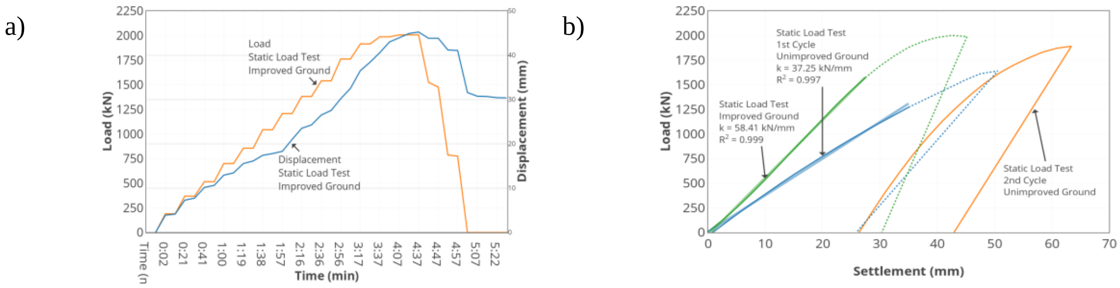
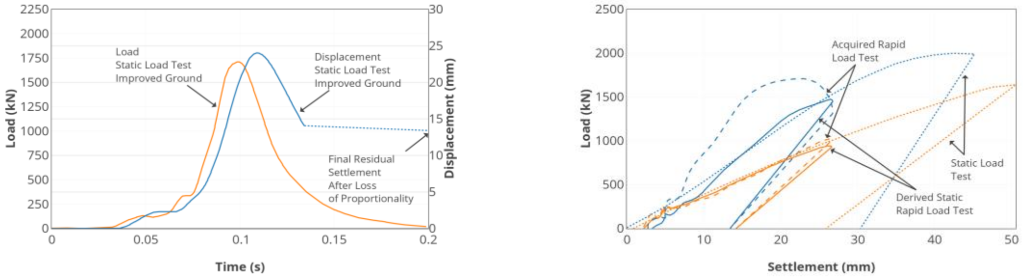


Figure 4. Static load tests results showing a) Variation of load and displacement with time and b) Load-settlement curves on unimproved & improved ground.

5 COMPARISON OF STATIC AND RPLT RESPONSE

RPLT tests were performed at locations adjacent to the static load test locations. A cushion comprised of alternating 25mm thick layers of Styrofoam and plywood was used at varying total thicknesses. The load-time history for any given blow was measured using a single load cell with a capacity of 5000 kN located in the center of the anvil. The acquired time histories are preprocessed by application of calibration constants, signal isolation, and noise filtering. Sample force and displacement time histories are shown in Figure 5a. ASTM D4945-00 mentions the need to monitor proportionality of force and displacement in the case of dynamic tests on piles. Dynamic load tests typically apply a force pulse duration of 10 to 30ms, whereas rapid load tests are performed over a longer period on the order of 50ms to 500ms. At these long durations, it is impossible to maintain proportionality indefinitely beyond the point of maximum displacement, and the loss of proportionality can be attributed to arrival of high frequency vibrations at the laser reference, and the tendency of accelerometers to drift when near stationary.

The Unloading Point Method (UPM), as described by Middendorp *et al.* (1992), was used in processing time histories and deriving an equivalent static load settlement curve from the RLT results. Multiple and single cycle RLT were performed. It was observed that the single cycle test methodology ensures that the result of the RLT corresponds to virgin soil that has not been disturbed by previous blows or loading cycles. Results on Figure 5b compare acquired load settlement curves (measured force versus settlement) with those obtained following application of the UPM method, and indicates an effective correlation level between the load settlement curve obtained by the static load test and the single cycle RLT curves (UPM).



(a) (b)

Figure 5. Rapid load test results showing a) Load and displacement variation with time and b) Comparison of static and rapid load tests results before and after improvement with stone columns.

The fact that the RLT-derived curves follow the static curve is very promising, despite the fact that the RLT curves fell short of capturing the full spectrum of load. Future tests at the site will aim at increasing the loading energy by increasing the drop height to try and achieve higher derived static loads on the footing.

6 SUMMARY AND CONCLUSIONS

The results presented in this paper demonstrate the promise of rapid load testing as a technique to evaluate compliance of shallow foundations with settlement specifications of ground improvement programs. One to one comparisons between results from static load tests and rapid tests showed that the RPLT constitutes a feasible testing method that could supplement quality control measures for foundations on improved or unimproved ground.

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