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Authors
Rivera, Alfonso J
Olgun, C Guney
McCartney, John S
et al.

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Centrifuge Tests on Laterally Loaded Footings Supported by Stiff Column-Reinforced Clay

Alfonso J. Rivera[1], S.M. ASCE, C. Guney Olgun[2], Ph.D., John S. McCartney[3], Ph.D., M. ASCE, P.E., Frederic Masse[4] and Thomas L. Brandon[5], Ph.D., M. ASCE, P.E.

[1] Ph.D. Student, Dept. of Civil & Environmental Engineering, Virginia Polytechnic Institute and State University, 111 Patton Hall, Blacksburg VA 24061; ariverar@vt.edu
[2] Research Assistant Professor, Virginia Polytechnic Institute and State University, Dept. of Civil & Environmental Engineering, 111A Patton Hall, Blacksburg, VA 24061; colgun@vt.edu
[3] Associate Professor, Department of Structural Engineering, University of California San Diego, 9500 Gilman Dr., 442J SEM, La Jolla, CA 92093-0085; mccartney@eng.ucsd.edu
[4] Vice-President of Engineering, Menard USA, 150 East Main Street Suite 500, Carnegie, PA 15106; fmasse@menardusa.com
[5] Professor, Dept. of Civil & Environmental Engineering, Virginia Polytechnic Institute and State University, 22 Patton Hall, Blacksburg VA 24061; tbrandon@vt.edu

ABSTRACT: An experimental study using centrifuge physical modeling was performed with the purpose of examining the lateral load behavior of stiff-column-supported footings. The lateral load behavior of stiff column-supported footings is currently poorly understood. Uncertainty exists regarding the performance of these systems under lateral loading. The results of the centrifuge tests suggest that one of the main components of a typical stiff column-supported footing system, the load transfer platform, plays an important role in determining the capacity and response of such systems under lateral loading.

INTRODUCTION

Stiff columns, a type of ground improvement technology, essentially reinforce the foundation subgrade in order to produce a composite soil/column matrix with improved mechanical properties. Stiff columns are constructed as part of a system that comprises the stiff column-reinforced soil, the loaded foundation and a granular mattress commonly referred to as a “load transfer platform” which is underlain by the reinforced soil (Figure 1). Typically, the stiff columns are installed through saturated, soft, compressible soil and embedded in dense sand, stiff clay, glacial till, or other competent material that serves as a bearing stratum. The stiff column-reinforced soil is used to support foundation systems such as footings, slabs and embankments. Recent interest has focused on examining the response of stiff column-supported footings to lateral loading. No guidance is available that describes the mechanics behind the lateral response of these types of systems. Sources of lateral loading can include, for instance, the lateral thrust behind retaining walls. This work presents a summary of the results of a centrifuge physical modeling testing program that was performed using the 15 g-ton, 1.36-m radius Genisco centrifuge at the University of Colorado Boulder with the purpose of examining the influence of the granular mattress or load transfer platform in the lateral load behavior of the stiff column-supported footing system. For completeness, details on the construction and testing of the centrifuge models are included as well.

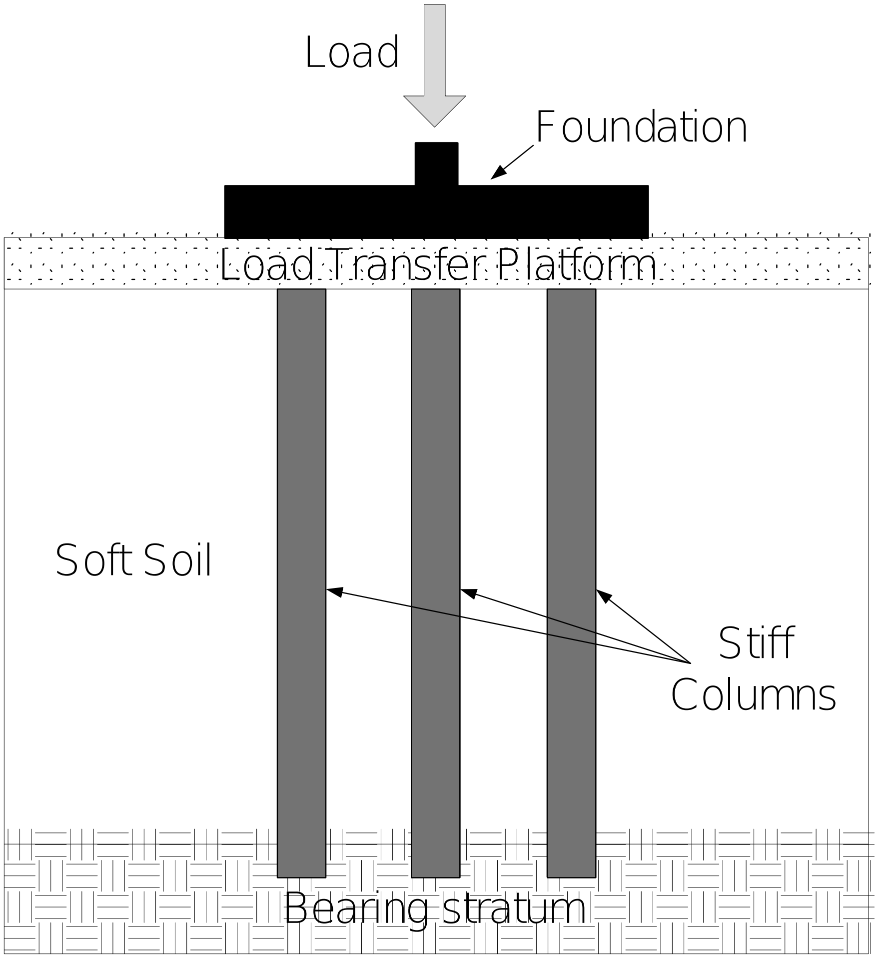

FIG. 1. Components of a stiff column-supported foundation system.

CENTRIFUGE TESTS

Layouts, Equipment and Materials

The 15 g-ton centrifuge of the University of Colorado Boulder was used in the centrifuge testing program. The centrifuge is capable of spinning a payload of 150 kg to 100g of centrifugal acceleration. The centrifuge has a symmetrical arm comprised of aluminum sections that carries swing-baskets at each end. Each basket can accommodate experimental payloads with a base area of 457 mm by 445 mm and a height of 584 mm (18 × 17.5 × 23 in). The reader is referred to Ko (1988) for further details of this centrifuge.

Four tests were performed at a 50 g-level. A four stiff column-square layout was tested in each model of the centrifuge testing program. The diameter of the columns at the prototype scale was 0.318 m and the width of the square footing was 2.40 m. An area replacement ratio of 5.5% was used in all the centrifuge models, a quantity within the range employed in practice (Buschmeier and Masse, 2012). The length of the columns inside the soft soil was 7.50 m and an additional 0.50 m was used for embedment in the bearing layer producing a total column length of 8.00 m. Different load transfer platform thicknesses of 0.45, 0.60, 0.70 and 1.20 m were considered for each centrifuge test. Figure 2 provides a summary of the geometry of the layouts tested at the prototype scale.

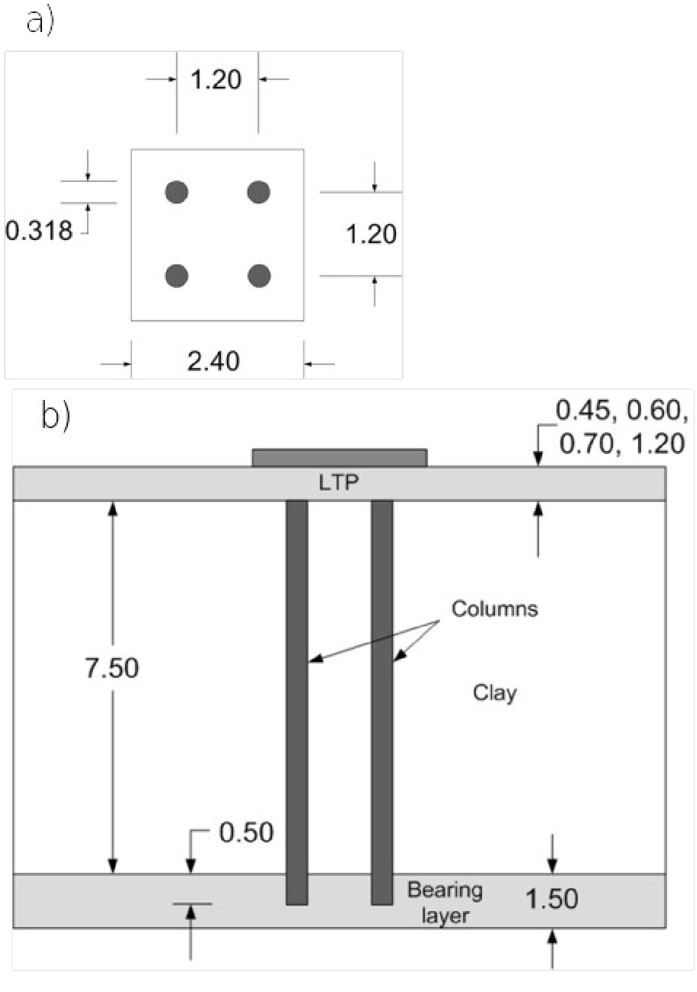

FIG. 2. Layouts tested in centrifuge testing program, a) plan view above footing and b) cross section – All dimensions in meters – not to scale.

The centrifuge models were constructed in two cylindrical containers. A porous stone was placed at the bottom of each container in order to provide drainage during the different consolidation stages. In addition, a drainage line was installed at the side of containers to redirect the water drained from the base to the top of the container. Additional equipment used throughout the centrifuge testing program included miniature pore pressure transducers (PPTs) that were used to monitor the development of excess pore-water pressures throughout the consolidation and testing stages of the centrifuge testing program. A linear variable deformation transformer (LVDT) was used to measure the lateral displacements of the model footing during lateral testing. A load cell was used to record load during lateral testing and during undrained shear strength measurements of the soft soil. A 7.60 cm × 1.10 cm T-bar penetrometer was used to measure the undrained shear strength of the soft soil. An actuator, powered by a motor located at a platform placed at the top of the centrifuge basket, was used to laterally load the model during testing. Data throughout the test was collected using a data acquisition system located in the rotational axis of the centrifuge. This centrifuge study used Speswhite clay to model the soft soil layer. The properties of this soil have been reported in the literature (Table 1).

Table 1. Properties of Speswhite Clay (Macari et al., 1987)

Index Properties	
Liquid Limit	53
Plastic Limit	32
Plasticity Index	21
Unified Soil Classification Scheme Designation	CH
Specific Gravity	2.66
Percent of minerals present	
Kaolinite	> 99
Illite	< 1

Nevada sand was the granular material used to model the bearing layer and the load transfer platform. Nevada sand is a fine, uniform granular soil. It minimizes particle-size scale effects in centrifuge testing due to the small size of its particles (Taylor, 1995). Table 2 summarizes the properties of the batch of Nevada sand used for this study.

Table 2. Properties of Nevada Sand

Soil	No. 100 Nevada Sand
Classification	Uniform, fine sand; SP
Grain sizes, D_{50}, D_{10} (mm)	0.13, 0.09
Coefficient of Uniformity, C_u	1.55

Coefficient of Curvature, C_c	0.96
Maximum Void Ratio, e_{max}	0.843
Minimum Void Ratio, e_{min}	0.555
Specific Gravity, G_s	2.65

Model Construction

The first stage of the construction of the centrifuge models consisted on the pluviation of the bearing layer. Nevada sand was rained from a height of 1.85 m over the cylindrical container in several passes, until a thickness of 30 mm (1.50 m in prototype scale) was reached. This procedure produced a bearing layer of Nevada sand with a relative density of 75%. Subsequently, the bearing layer was saturated and the clay slurry was prepared. The Speswhite clay in powder form was mixed with water such that it resulted in a slurry with a water content equal to two times the liquid limit of the clay, or w(%) = 2LL. After mixing, the slurry was placed inside the container in three lifts (with the exception of one test in which only a single lift was placed). Each previous lift was preconsolidated at 1G under a dead-weight surcharge of 5 kPa before the placement of subsequent lifts.

Once preconsolidation of all three layers of clay at 1G was finished, the container was placed inside the centrifuge basket for in-flight self-weight consolidation at 50G. This procedure produced led to a clay layer that was nearly normally consolidated clay layer with depth, with the exception of a thin overconsolidated portion at its top due the effects of the dead-weight surcharge. Before centrifugation, the T-bar device was attached to the reaction frame above the container so that it could be used to evaluate the undrained shear strength distribution with depth for the soft soil after completion of the in-flight self-weight consolidation stage. During centrifugation, excess pore-water pressures were monitored throughout this stage and consolidation was finished until t_{90} was reached. After t_{90} was reached and consolidation was considered to be completed, the T-bar was lowered into the soil in order to measure the undrained shear strength of the clay. The T-bar was lowered at a rate of 1 mm/sec which is sufficiently fast to result in undrained loading conditions in the soft clay layer (Lehane et al., 2009). Using a bar factor of 10.5 and the nominal diameter of the T-bar, the axial force measurements recorded by the load cell were expressed in terms of the undrained shear strength using the approach of Stewart and Randolph (1994).

The results of the measurements of undrained shear strength with depth in the centrifuge tests that were performed are summarized in Figure 3. With the exception of the test with a load transfer plotform thickness of 0.70 m which corresponded to the test in which a single thick lift was preconsolidated, the undrained shear strength profiles obtained for the rest of tests fall within a narrow and consistent range.

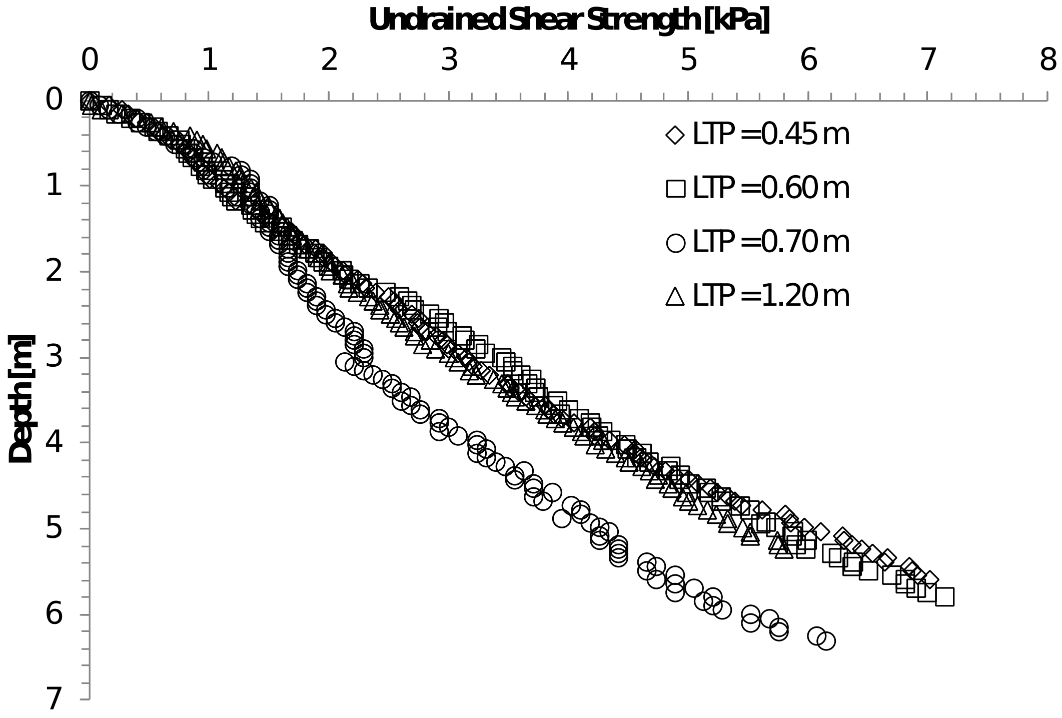

FIG. 3. Undrained shear strength profiles in clay layer after self-weight consolidation at 50g.

After the in-flight self-weight consolidation stage was completed, the container was removed from the centrifuge and the model columns were constructed and installed in the soft soil. The columns were constructed using a neat mix of water/cement at a ratio of 50% by weight. Portland cement type I/II was used in the mix. The mix was injected into straws that functioned as formwork. The formwork had a prototype diameter of 0.318 m. The formwork/mix elements were later placed in a vibrating table in order to remove bubbles from the mix. Then the formwork elements were placed in a container with water for curing. After 48 hours of curing, the columns were removed from the formwork and using a file, the columns were reduced to the appropriate length. The columns were later installed in the soil at 1G.

After the columns were installed in the soft soil, the granular load transfer platform was pluviated in dry conditions above the column-reinforced soil. Different load transfer platform thicknesses were selected for each lateral test. The load transfer platform was pluviated from a height of 1.85 m and similar to the bearing layer, this produced a load transfer platform with a relative density of 75%. After the load transfer platform was finalized, the container was placed inside the centrifuge and the model was consolidated in-flight at 50G under the added weight of the load transfer platform. After this stage was completed, the container was removed from the centrifuge and preparations were made for lateral load testing of a footing placed atop the load transfer platform .

Lateral Testing

Figure 4 provides a schematic of the lateral loading procedure employed in each centrifuge model. The setup as observed in the figure consisted of a cable attached to the footing via a load cell attached to the side of the footing. The footing itself was subjected to a constant vertical load of 620 kN that includes a series of dead weight attached to its top and its own self-weight. The cable was guided through a series of pulleys until it was attached to the vertical actuator as shown. Then the actuator was lowered at a constant rate of 0.1 mm/sec. Lowering of the actuator essentially laterally loaded the square footing due to the arrangement of the cable through the pulleys. The lateral tests were performed in-flight at 50G. Lateral loading was monitored through a camera mounted on the top of the model. After the test was completed, the model was removed from the centrifuge and it was proceeded to reduce the data recorded.

RESULTS

Figure 5 summarizes the lateral load-displacement behavior of the lateral tests performed. Yield or failure for each of the lateral load-displacement curves shown in this figure was defined using a work criterion in which the accumulated area beneath the curve i.e. the accumulated work is plotted against the lateral load measured. Based on this procedure, the yield point for each test was identified.

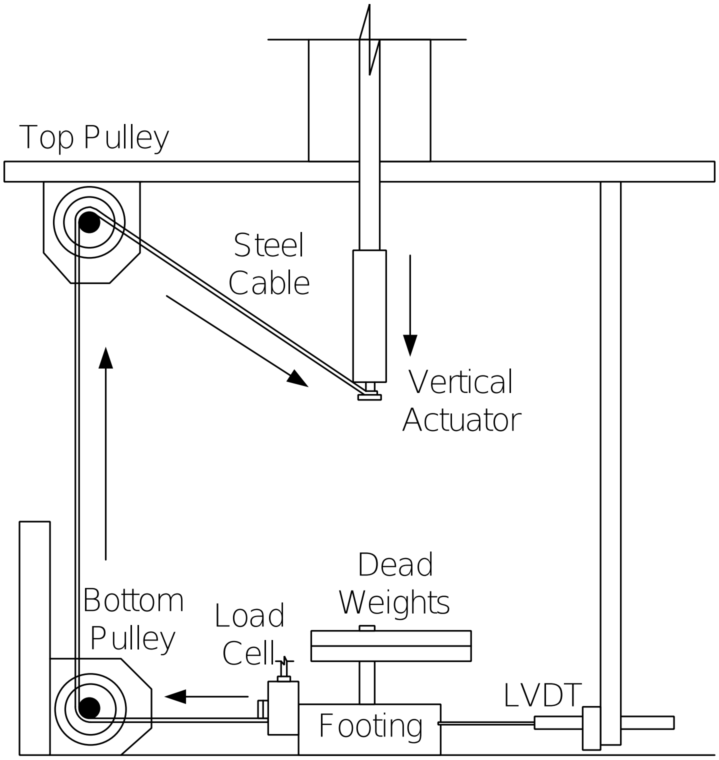

FIG. 4. Schematic of the lateral loading procedure employed on the stiff column-

supported footing system.

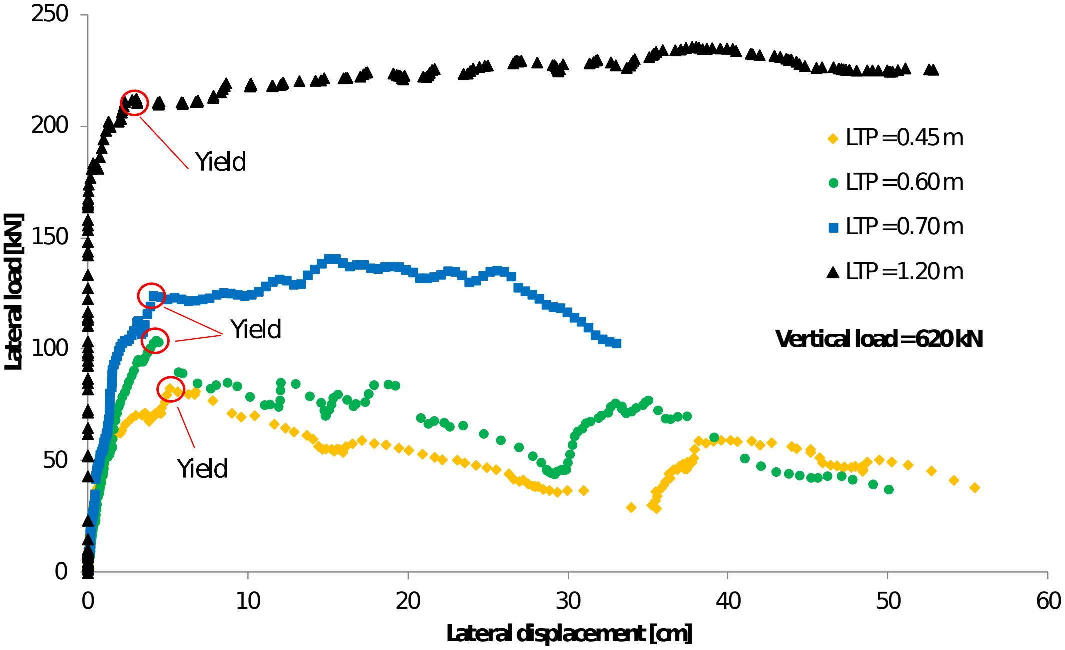

FIG. 5. Lateral load-displacement behavior of lateral load tests for different load transfer platform thicknesses.

The yield loads previously estimated for each test in Figure 5 were plotted against the load transfer platform thickness in Figure 6. These results can be used to assess the influence of this component on the lateral capacity of the stiff column-supported foundation.

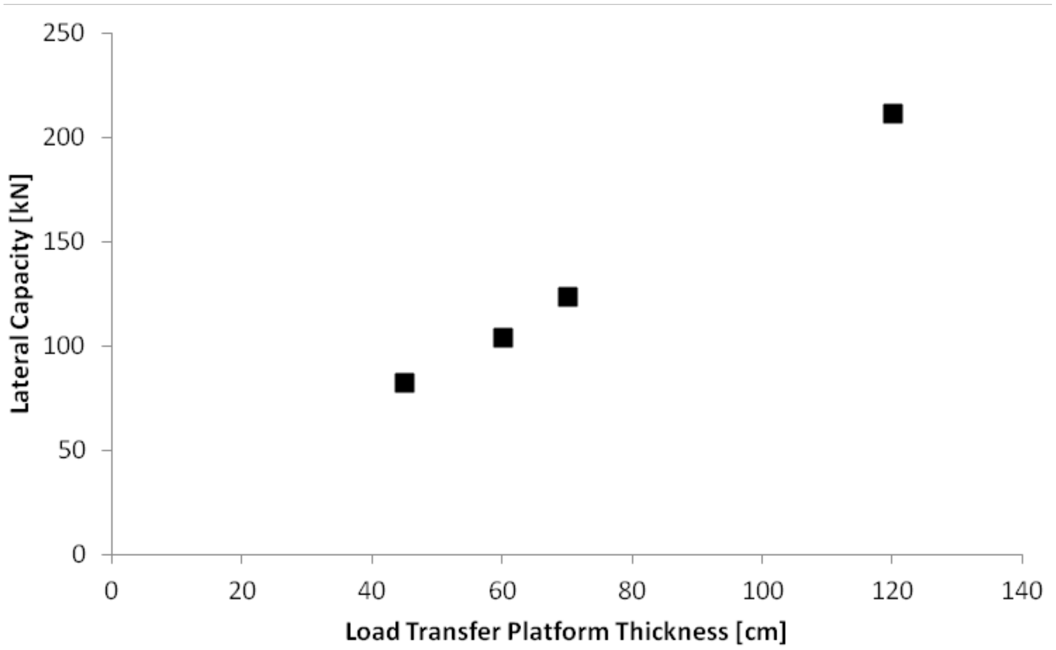

FIG. 6. Influence of the load transfer platform thickness on the lateral capacity of the stiff column-supported footing system.

Several conclusions can be drawn from the results shown in Figures 5 and 6. For instance, from Figure 5, the lateral capacity of the laterally loaded stiff column-supported foundation system as indicated by the yield load for each lateral test increases with increasing load transfer platform thickness. This trend is confirmed in Figure 6. The lateral capacity of a laterally loaded stiff column-supported foundation with a load transfer platform thickness of 1.20 m is approximately 2.5 times greater than the lateral capacity of a stiff column-supported foundation with load transfer platform thickness of 0.45 m. In other words, the lateral capacity of the system increased 2.5 times in a span of 0.75 m of load transfer platform thickness. When examining the initial pre-yield lateral load-displacement response, it can be observed that this response is nearly infinitely stiff when the load transfer platform thickness is equal to 1.20 m and for subsequent less thick load transfer platform, the stiff response decreases. In the case of the post-yield lateral load-displacement behavior, less softening occurs with increasing load transfer platform thickness. The above results, suggest that the thickness of the load transfer platform plays an important role in controlling the lateral loading behavior of footings resting on stiff column-supported footing systems.

CONCLUSIONS

A study was conducted with the purpose of examining the lateral load behavior of stiff column-supported footing systems using centrifuge testing. Four centrifuge tests were performed and in each test, different load transfer platform thicknesses were considered. The results from this centrifuge study indicate that the load transfer platform can control the lateral response of the stiff column-supported footing, and more specifically it was observed that an increasing load transfer platform thickness, increased the lateral capacity of the system, produced less post-yield softening response and a stiffer pre-yield response.

ACKNOWLEDGEMENTS

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