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Experimentally-derived cyclic P-Y Curves for rigid walls supporting granular backfill

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ABSTRACT: For structures with basement walls, the interaction between the soil and the walls affects the response of the system. In the context of performance-based design, there is interest in quantifying the relationship between the lateral earth pressure and the wall displacement using p-y curves. To date, limited studies were conducted on the mobilization of lateral earth pressure under cyclic loading. For most cases, p-y curves were assumed elastic-perfectly plastic with active and passive conditions reached at wall displacements of 1.3mm and 13mm, respectively. In reality, the relationship between lateral earth pressure and wall displacement is complex. This paper presents results from an experimental program that aims at measuring the cycled p-y response of rigid walls that are supporting granular backfill. A steel rigid wall is instrumented with sensors to record the development of earth pressure during active and passive displacement cycles. The outcome is a set of measured p-y curves that portray the effect of displacement history on the development of earth pressure.

1 INTRODUCTION

The mobilization of lateral stresses behind retaining walls constitutes a typical soil structure interaction (SSI) problem. For structures with underground basement walls, the interaction between the adjacent soil and the walls affects the response of the system, particularly under cyclic loading conditions. In the context of performance-based design, there has been interest in quantifying the relationship between the lateral earth pressure and the wall displacement by using the p-y curve method, which aims at replacing the homogeneous soil continuum by a series of springs that mimic the soil behavior. The p-y method has been advocated and applied by geotechnical and structural engineers in the design of laterally loaded piles. However, the use pf p-y curves for the analysis of rigid retaining walls is still in its early stages. There is a need for realistic and simplified models that could describe the p-y relationship for rigid walls, to be used as input in robust soil-structure-interaction problems. The work presented in this paper is a step taken towards satisfying this need.

The earlier investigations on p-y curves for laterally loaded piles involved experimental tests for piles embedded in clay (Matlock 1970) and sand (Reese et al. 1974). These earlier works targeted the effect of cyclic loading on the resulting p-y response for piles in clay and sand, respectively. The problem of laterally loaded piles has since been extensively studied using full scale field tests, centrifuge tests, and 3D finite element analyses. Conversely, very limited studies have been conducted on the mobilization of lateral earth pressure behind rigid walls under cyclic loading in the context of p-y curves. In the absence of such studies, semi-empirical p-y models have been used in the literature for investigating the structural response of buildings with basement walls under seismic loading conditions. Briaud and Kim (1998) were the first to recommend p-y relationships for the analysis and design of tie-back walls. These p-y relationships were calibrated/back calculated using data collected from full scale tests on walls in sand. Briaud and Kim (1998) state that the lateral earth pressure that is exerted by the soil on the wall is bounded by the active and passive earth pressure conditions. Based on the data collected, they recommend that the active earth pressure could be assumed to be mobilized at wall movements of 1.3mm (away from the retained soil) while the passive resistance could be mobilized at a wall movement of 13mm (into the retained soil). El Ganainy and El Naggar (2009) and Saad et al. (2016) adopted this p-y relationship as the "backbone curve" for the lateral pressure-lateral deflection relationship used for modeling the embedding soil in their analysis of the response of buildings with underground stories. Richard et al. (1999) also recommended that the soil be modeled by a series of springs having a bilinear p-y curve consisting of an elastic portion bounded by upper and lower limits defined by active and passive state, with the recommended elastic stiffness that defines the p-y response being a function of the square root of depth.

In reality, the relationship between lateral earth pressure and wall displacement is expected to be complex, nonlinear, and affected by the height of the wall, the relative density of the back-fill material, the interface friction between the wall and the soil, the nonlinearity of the soil response, and the type of wall movement (translation and/or rotation). In an attempt to study the complexities associated with modeling the p-y response, Elchiti et al. (2017 and 2018) utilized a two-dimensional PLAXIS model to investigate the static/monotonic soil-structure interaction between rigid walls and sand backfill using finite element analyses for active states of loading, while enforcing a realistic modeling of the soil support at the base of the wall. The main goal was to identify and characterize the components of the p-y relationship at different depths with particular emphasis on the effects of the interface friction angle between the wall and the soil. The results of the numerical simulations showed that the static p-y response was highly non-linear, depth dependent, and sensitive to the interface friction coefficient, wall height, and density of the sand.

The above background points to two main limitations in the current understanding of a p-y model for the response for walls supporting granular soils: (1) the current knowledge is limited to the static/monotonic p-y response with no published experimental or numerical work on the effect of multiple loading cycles on the predicted behavior, and (2) there are currently no experimental studies that attempt to investigate the p-y response of walls subject to monotonic or cyclic lateral movements. The main goal of the work presented herein is to provide a first step towards a comprehensive investigation of the p-y response of granular soils that are supported by rigid retaining walls, over the full range of wall displacements (active to passive) and under cyclic loading conditions. This goal is to be achieved experimentally by designing and constructing a laboratory-scale retaining wall prototype that could be used to measure the p-y response for granular soils under static and cyclic loading conditions. The conceived and built experimental setup is presented in this paper, along with preliminary results that were obtained from a test conducted on a wall supporting medium dense sand. The results are presented in the form of cyclic p-y curves.

2 EXPERIMENTAL SETUP

A rigid steel wall was constructed in the laboratory as a prototype for the testing program. The width, length and height of the prototype were chosen as 0.5m, 2.6m, and 1.2m, respectively (Figure 1). The front wall, 0.5m wide x 1.2m high, is hinged at its bottom allowing it to freely rotate about its base. The length of the prototype was carefully chosen such that (1) it would be sufficient to allow for the passive failure-wedge to develop within the retained sand and (2) no pressures will develop at the back wall that will cause unwarranted confinement pressure at the front wall. Once the wall dimensions were selected, a 3D prototype was modeled on a structural software to investigate the development of stresses and deformations on the side walls. Based on the structural analysis, the wall was designed to limit the side wall deformations to a maximum lateral deflection of 1mm both during filling and upon the mobilization of passive conditions. A 1mm lateral deflection was considered sufficient to simulate plane-strain conditions along the side walls.

One of the major challenges in conducting retaining wall experiments within the context of laboratory setup is the development of frictional stresses at the side walls. Several methods are

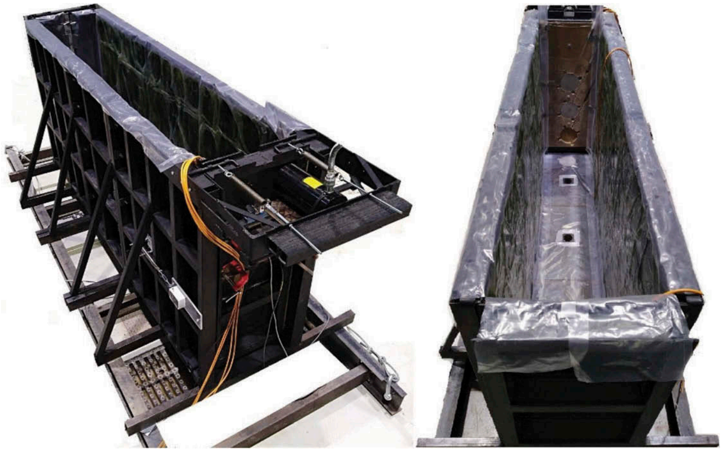

Figure 1. Rigid wall prototype

presented in the literature that aim at minimizing frictional stresses at the interface between soil and other material (Tatsuoka et al. 1985 & Fang et al. 2003). These studies show that shearing soil against an acrylic plate while separating both materials by grease or thin layers of plastic sheets yields low interface friction angles. Silicon grease is used at the soil-acrylic plate boundary to reduce the interface friction angle. To keep the soil clean and uncontaminated by the grease

layer, a thin latex sheet is used to separate the soil from the grease. This method yields interface friction angles that are inversely related to the applied confinement pressures. At confinement pressures exceeding 10 kN/m^2, the interface friction angle could be as low as 3 degrees (Fang et al. 2003). Another method uses different layering sequences of thick and thin plastic sheets over an acrylic plate to reduce the interface friction.

While the latter can be quicker, more economical, and cleaner than the grease method, it yields higher interface friction angles reaching values between 10 to 15 degrees for most plastic sheet sequences. As a result, the grease method was adopted for the setup developed for our work. The prototype sidewalls were first overlain with a 4mm PLEXI-glass plate. A layer of grease was applied over the PLEXI glass plate and then covered with a thin plastic sheet.

Four Geokon 4800 pressure sensors were mounted at depths of 25cm (Sensor 1), 50cm (Sensor 2), 75cm (Sensor 3), and 100cm (Sensor 4) on the inside of the front wall to record the lateral earth pressures. To quantify the residual frictional forces developing at the sidewall, a setup was designed to read the tangential force developed at the sidewall-grease interface at a specific location. Across from it, a load cell was attached to record the normal force acting on the opposite sidewall and at the same location/height. Measurements of the tangential force and normal force allowed for the back-calculation of the interface friction angle developing at the side walls during the tests. Dry sand with properties shown in Table 1 was used for the experiment.

Table 1. Soil Properties

Properties	Values
Specific Gravity	2.69
Angle of Friction (°)	48
Percent Fines (%)	<1
Unit Weight (kN/m^3)	16.2
Relative Density	0.6

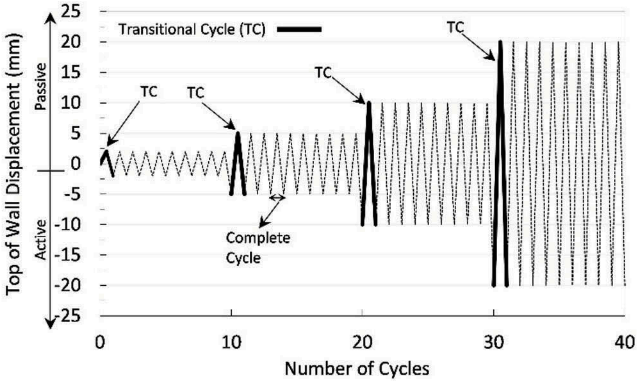

Figure 2. Cyclic experimental program

3 TESTING PROGRAM

The experimental program involved subjecting the top of the rigid wall to 40 consecutive cycles of lateral top wall displacement sub-divided into four intervals: ±2mm (0.17% drift), ±5mm (0.41% drift), ±10mm (0.83% drift), and ±20mm (1.67% drift). The cyclic testing program is summarized in Figure 2. Each displacement interval was cycled 10 times before moving to the higher interval. A complete cycle was defined by the distance the wall moves between two consecutive lower bounds of a given interval. A cycle consists of a passive wall movement (wall moves into the backfill) followed by an active wall movement. When the number of cycles in a given interval was completed, the wall was moved to the lower bound of the next displacement interval and a new set of cycles initiated. The 1st cycle in the new displacement interval is referred to as a transitional cycle. Transitional cycles are marked on Figure 2 by a heavy solid line.

A displacement-controlled hydraulic piston, capable of moving at 0.01mm increments, was used to move the top of the wall horizontally. In order to limit the frictional sidewall forces to the lowest levels possible, the rate of top-wall movement was carefully selected by monitoring the readings of the friction sensor at the sidewall. Following each displacement increment, the hydraulic piston was stopped and the system allowed to rest (dissipate built-up frictional stresses at the sidewalls) before the lateral earth pressure was noted. This was repeated at every wall location were the lateral earth pressure was recorded.

The sand was deposited in uniform layers by a hand-operated air pluviation using a specifically designed traveling hopper. The relative density of the deposited soil is affected by the deposition intensity (DI), the height of fall (HF), uniformity of sand rain, and size of particles (Dave et al. 2012 & Tabaroei et al. 2017). The deposition intensity is defined as the mass of soil deposited per unit area per unit time while the height of fall is taken as the distance from the bottom tip of the pluviator to the mid height of each successive layer. Several experiments were conducted on a miniature box with varied DI and HF and the resulting soil densities were recorded. An HF of 35cm at a DI of 35.3 g/cm^2/s were used to produce a dry sand density of 1650 kg/m^3 (RD = 60%). Once the HF and DI were determined, the rigid wall prototype was then filled in successive 5cm layers of dry sand. Throughout the filling process the hand-held pluviator was kept straight to ensure a uniform discharge of sand while being manually moved at an approximate velocity of 2 meters per minute across the prototype bed. When the prototype was completely filled, the average density of the fill was back-calculated from the total weight of soil dropped and the retained volume and was found satisfactory.

4 RESULTS AND ANALYSIS

Figures 3 and 4 depict the behavior of the retained soil at Sensor 2 (located at a depth of 50 cm) as the rigid wall is cycled between the four displacement intervals. Figure 3 shows the p-y

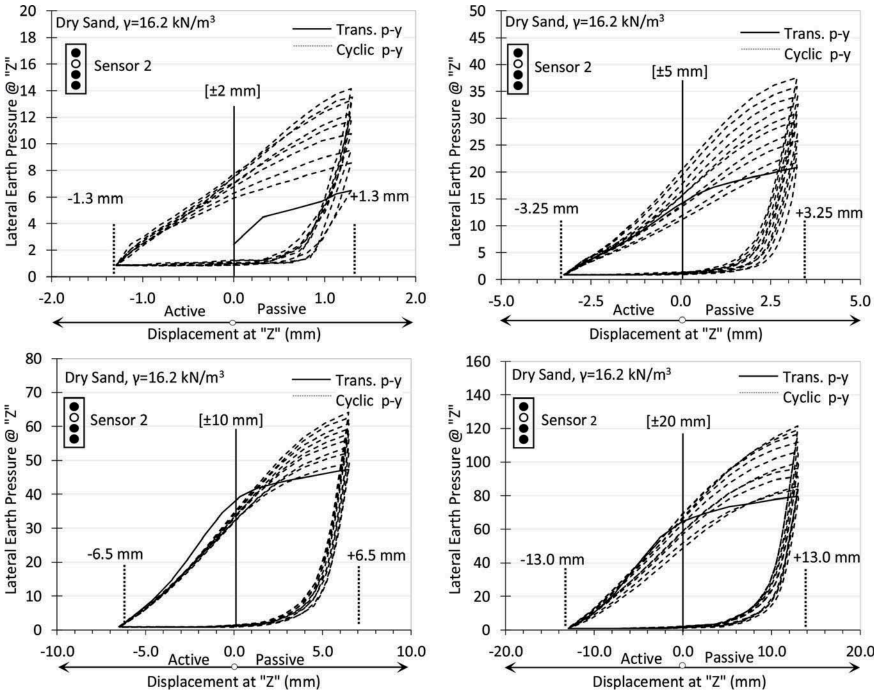

Figure 3. Cyclic p-y curves recorded at Sensor 2 for ±2, ±5, ±10, and ±20mm intervals

curves while Figure 4 shows the variation of the earth pressure coefficient k with wall displacement. Results from other sensors are not reported in this paper due to length limitations. Note that Sensor 2 moves only a fraction of the displacement prescribed to the top of the rigid wall as indicated by two vertical lines extending from the horizontal axis in Figures 3 and 4. An investigation of the cyclic p-y curves that are presented in Figures 3 and 4 leads to several interesting observations.

First, the observed p-y curves that describe the response of the soil as the wall is moved in the passive and active directions are highly non-linear for all magnitudes of displacement intervals. This observation is in line with finite element results presented in Elchiti et al. (2017, 2018) for the active response. This indicates that simple elastic-perfectly plastic p-y models may not be representative of the actual lateral earth pressure response of sands during cyclic loading. More importantly, the results point to the importance of cyclic loading on the overall p-y response. At any given wall displacement in the passive direction, the lateral stress behind the wall is found to increase incrementally following each wall movement cycle. The first and last passive p-y curves of each interval are selected and plotted on Figure 5. Results indicate a significant increase in the maximum pressure at the passive side ranging from 30.3% to 68.6% after 10 loading cycles. The largest increases are noted for the cases of small displacement intervals (±2mm and ±5mm) which seem to have benefited the most from cycled loading. The improved p-y response as a result of cyclic loading for this medium dense sand may be associated with a process of densification of the sand with repeated loading cycles

Second, an examination of the p-y response in the unloading portion of the p-y curves (passive side to active side) indicates that the lateral stress drops at a very fast rate as the direction of wall movement is reversed from passive to active. The rate of decrease in the lateral stress seems to be insensitive to the number of loading cycles, with the unloading sections of the p-y curves showing remarkable consistency between cycles. The shape of the active section of the p-y curve is "hyperbolic" and consistent with numerically derived curves as reported in Elchiti et al. (2018). The transition from the "passive" to the "active" side is characterized by an initial sharp decrease in lateral stress followed by a gradual reduction in stiffness leading eventually to

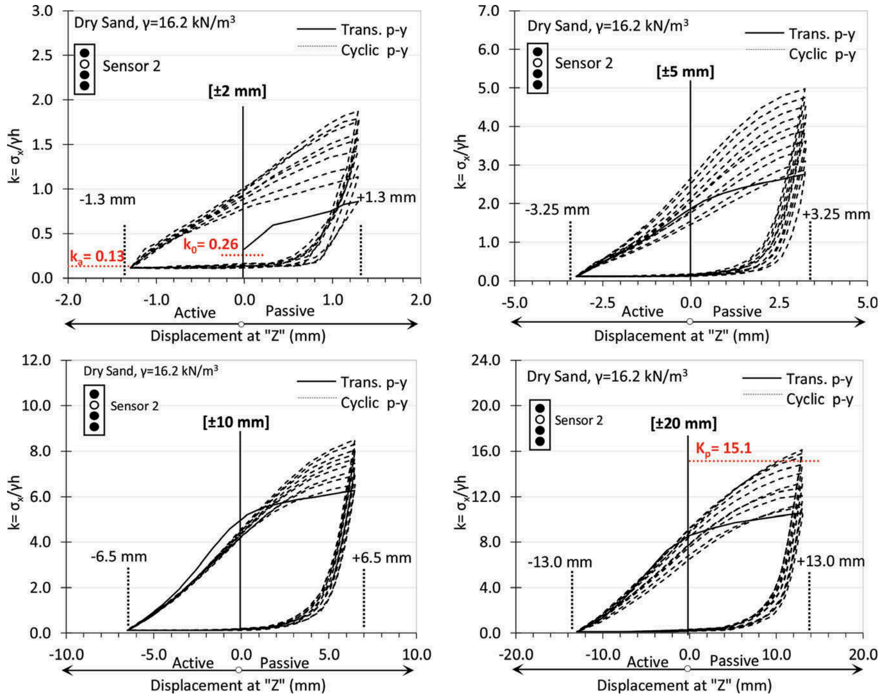

Figure 4. Soil coefficient k recorded at Sensor 2 for ±2, ±5, ±10, and ±20mm intervals

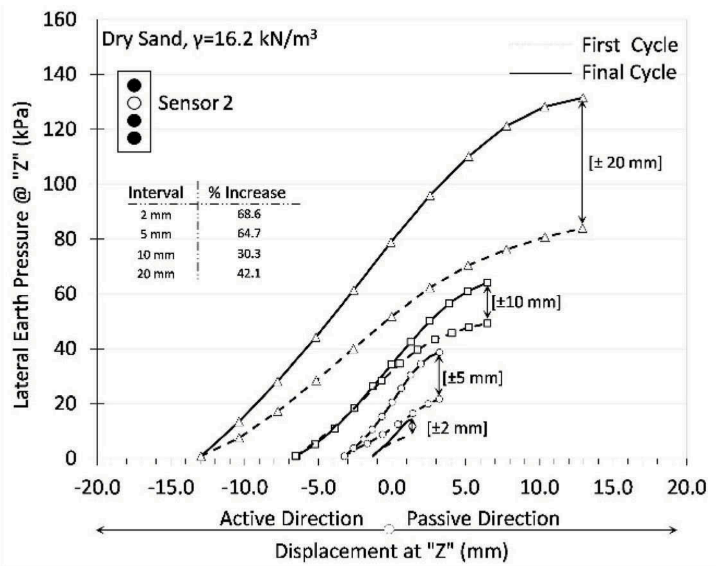

Figure 5. Difference in passive p-y curves between 1st and 10th cycle

the mobilization of full active conditions behind the wall. It is interesting to note that the wall displacement required for the lateral stress to reach active conditions increases as the range of the displacement interval increases. At the location of Sensor 2, the wall displacement needed to reduce the maximum stress to the fully mobilized active stress increases from about 1mm for the 2mm displacement cycles to around 10mm for the 20mm displacement cycles.

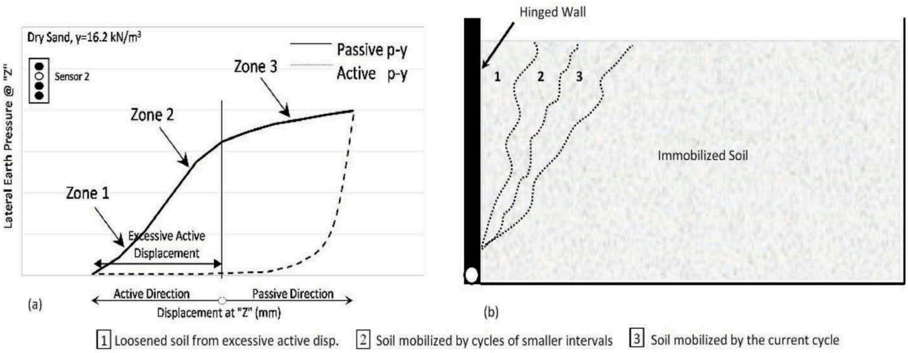

Figure 6. (a) Typical p-y cycle (b) Formation of zones of different soil densities due to cyclic loading

Third, there is an increase in the earth pressure coefficient "k" with each wall cycle. Figure 4 plots the variation of the coefficient "k" versus the wall displacement at Sensor 2 as the wall is cycled between the targeted intervals. As shown in the figure, "k" not only increases with passive wall displacements but also increases with wall cycles within each cyclic interval.

The at-rest, active, and passive earth pressure coefficients, k_o, k_a, and k_p, were calculated for a sand friction angle of 48° and plotted on the first and last plots in Figure 4. The calculated values of k_o, k_a, and k_p are 0.26, 0.13, 15.1 respectively. k_a and k_p were computed using Coulomb's earth pressure theory assuming a wall interface friction angle of 15°. It can be seen that the three theoretical values of 'k' compare well with those backed-calculated from the experiment. Moreover, results for the passive cycles indicate that the passive conditions were only reached after numerous cycles and relatively large wall displacements.

Fourth, the results show a clear difference between the response of the transitional p-y curve (the first loading curve in a new displacement interval) and the rest of the curves. Transitional passive p-y curves show an approximate bi-linear p-y response (solid lines) while the rest of the p-y curves are represented by "s-shaped" curves. The formation of "s-shaped" p-y curves in soil-structure-interaction problems that involve cyclic loading has been observed by others (Yankelevsky 1989). A typical s-shaped curve is shown in Figure 6a. Possible explanations for the formation of the "s-shaped" p-y response focus on the formation of three distinct zones of different soil densities just behind the moving wall (Figure 6b) as a result of cyclic movements. Zone 1 is a zone of loose soil formed by excess active wall movement in a previous unloading cycle. Excess active displacement denotes wall movement in the active direction beyond the displacement needed to mobilize the active limit state. Zone 1 contains soil of least density among the three zones. Zone 2 represents the soil affected by the loading/passive cycle of the previous interval and is expected to contain soil of the highest density among the three zones. Zone 3 represents soil that is being affected by the current interval displacement and contains a soil density equal to that of the undisturbed soil in the bed (initial density). As indicated in Figure 5a, the shape of each segment of the s-shaped curve can be attributed to straining soil in each of the aforementioned zones. It is worth noting that the reduced stiffness that is exhibited in the transitional p-y curve could be explained by the shifting of zone 3 to new regions of immobilized soil at the new drift level of wall displacement. This leads to the redefinition of zone boundaries resulting in a drop in passive soil stiffness in the following p-y curve. As for the rest of the passive p-y curves, a gradual increase in stiffness with each cycle is recorded as indicated previously.

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