CPT Assessment of Boundary Effects in Dynamic Centrifuge Modelling

Berrak Teymur
University of Cambridge, U.K.

S. P. Gopal Madabhushi
University of Cambridge, U.K.

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Berrak Teymur
University of Cambridge
Cambridge-UK CB2 1PZ

Dr. S.P.Gopal Madabhushi
University of Cambridge
Cambridge-UK CB2 1PZ

ABSTRACT

Dynamic centrifuge modeling requires special boundary conditions in order to minimize the effects of model containers on the performance of the soil within them, especially due to reflection of stress waves. This concern has lead to the development of the Equivalent Shear Beam (ESB) model container, which matches container stiffness to that of the soil column, the performance of which is evaluated in this paper. A series of centrifuge test involving loose and dense, dry and saturated models of homogeneous horizontal sand layers have been carried out, and measurements taken to quantify the effects of the boundaries on soil behaviour. Miniature Cone Penetration Tests (CPT) were conducted in flight, before and after earthquake loading to investigate boundary effects on the densification of sand near the end walls during dynamic loading, and arching of soil and shear transfer to the end-walls. The influence of boundary effects is shown based on centrifuge test data by comparing CPT profiles adjacent to the end walls with those taken near the center of the model container. The results verify the uniformity of the soil model prior to earthquake loading. Also they show that the penetration resistance changes after the earthquake loading. In case of loose dry sands, there is densification at the boundary relative to the center of model. In case of loose saturated models, the densification occurred at the middle of the model relative to the boundary region.

INTRODUCTION

Dynamic centrifuge modeling involves testing of reduced scale models in the increased gravity field of a geotechnical centrifuge. Due to the insufficient in-situ data on earthquake related geotechnical engineering problems, dynamic centrifuge modeling technique is important. Even though the principles of the earthquake model experiments are well explained in literature (Schofield, 1981), the boundary effects created by artificial boundaries of a model container need attention. During earthquakes strong ground shaking takes place producing additional stresses and strains in the foundation soil and in overlying structures. The ground vibration caused by an earthquake is the result of the transmission of stress waves from the bedrock. Dynamic centrifuge modeling requires special boundary conditions in order to minimize the effects of model containers on the performance of the soil within them, especially due to reflection of stress waves. The artificial boundary of a model container may cause distortion in the stress and strain field in the model compared with the prototype being modeled. The boundary effects created by the rigid and smooth end walls of a model container when compared with an infinite soil layer in the prototype suffer from the strain and stress dissimilarity and generation of P-waves (Zeng and Schofield, 1996). Accurate boundary conditions in the model are necessary. This concern has lead to the development of the Equivalent Shear Beam (ESB) model container, which matches container stiffness to that of the soil column, the performance of which is evaluated in this paper. In a model test it is important to have correct complementary shear stresses on end-walls of a specimen. If the walls were smooth, there would be no complementary shear stresses and rocking moments could be generated due to variation in vertical pressures (Madabhushi et al, 1995). Ideal boundary conditions were summarized by Zeng and Schofield (1996) as to minimise the container wall interference on the soil response, therefore it would involve no reflection of stress waves from the boundaries of the container. This implies that end wall displacements must be matched to those of the soil column and complementary shear stresses induced by base shaking must be sustained by the end walls of the model container. Boundaries parallel to the shake direction must be frictionless and allow zero lateral strain in order to satisfy the K_0 condition. The response of the soil to input shaking at its base would be controlled by the soil rather than the box properties.

The ESB model container has flexible frictional end-walls designed to move together with the soil inside and to sustain the complementary shear force induced by base shaking. It was designed to achieve the same deflection and natural frequency as an ideal prototype soil layer with thickness, H=10m, void ratio, e=0.77 (I_D=50%) with unit weight, γ=15kN/m3 and an earthquake of 30% at 50g. If ESB container is used for tests other than 50g, an error will be induced due to the increased stiffness of soil under increased g-level which will not be matched by the end-walls (Madabhushi et al, 1998). The dimensions of the ESB container are 560mmX250mmX223mm built with alternating rectangular layers of aluminum and rubber. Special features include inextensible friction sheets attached to each end-wall. These 0.5mm thin aluminum sheets were roughened by gluing sand onto them to transfer the shear stresses to the base of the container to overcome the overturning moment created in compression and extension. Some concerns about the ESB has lead to this research where full liquefaction occurs there is ambiguous data acquired near the end-walls as was observed by Peiris (1998). Peiris (1998) states that when the saturated sand inside the ESB model container liquefies, there is a region near the end walls where the sand retained its strength without liquefying caused by the incompatibility of the motion of the saturated sand near the end-walls. It is necessary to quantify this region so that when ESB model container is used in models of saturated sands, correct observations can be made. As one of the conclusions reached by Zeng and Schofield (1996), their research indicated limitations of the box firstly, in creation of local arching due to rubber layers affecting the stress distribution near the end-walls. Secondly, since the container is designed to have the same average stiffness as a soil layer in the design earthquake and the stiffness of soil changes with void ratio, effective stress and strain in the soil during earthquake tests. Therefore the stiffness of the soil changes while the stiffness of the container remains fixed, the box is only appropriate to use in conditions in which the change of soil stiffness is within a certain limited range. Therefore the research in this area, to quantify the changes in soil behaviour with various void ratios, effective stresses is needed to use the container for various experiments. Currently quantification of this effect and guidelines for appropriate use of the ESB container is not available.

A series of centrifuge tests involving loose and dense, dry and saturated models of homogeneous horizontal sand layers have been carried out, and measurements taken to quantify the effects of the boundaries on soil behaviour. Miniature CPT tests were conducted in flight, before and after earthquake loading to investigate boundary effects on the densification of sand near the end walls during dynamic loading may be impeded due to arching and shear transfer to the walls. The influence of boundary effects will be shown based on centrifuge test data by comparing CPT profiles adjacent to the end walls with those taken near the center of the model container. Research needs to be performed to study and to remove ambiguities in boundary conditions of ESB model container and experimental variability needs to be quantified. This paper describes an investigation of boundary effects associated with the Equivalent Shear Beam (ESB) container by means of miniature CPT soundings taken before and after the earthquake loading at different locations. The ESB container was developed to reduce boundary effects by means of a flexible, laminated end-walls, the shear stiffness of which can be adjusted to match that of the soil. The performance of the ESB box needs to be verified.

CPT RESEARCH ON SAND MODELS

Objective of CPT Tests

Cone penetration tests (CPT) are used in-situ increasingly due to their simplicity, speed and continuos profiling. Miniature CPTs are often used in centrifuge tests to obtain information on the homogeneity of sand models and the strength distribution. CPT was used by Sharp et al (1998) on the correlation of permanent lateral ground deformation (D_H) due to earthquake-induced lateral spreading caused by liquefaction of saturated sand, with CPT point resistance. D_H measurements were directly correlated with the CPT in centrifuge model tests for various sand relative densities and degrees of pre-shaking in their work. The objective of the current research reported in this paper is to study the effect of the earthquake loading and the proximity of end-walls on the measured cone resistance. Therefore measurements were taken before and after the earthquake at the center of the container and near the end-walls of dry and saturated sand models. The first objective of the cone penetrometer test was to verify that the model was uniform by penetrating the cones at about 135mm away from the end-walls. The penetration tests were performed at different parts of the soil at 4, 20, and 50 times the diameter of the probe from the end-wall. The CPT was used for comparison of the results since only total penetration resistance is logged. This of course would consist of both shaft friction as well as end bearing components. Since penetration resistance at different locations and at different times (i.e. before and after earthquake loadings) were compared, it was felt that the shaft friction and end bearing components need not be measured separately. When deciding on the places of penetration and regions affected by boundaries of the container the guidelines suggested by Gui et al, 1998 was followed. The ratio S/B of the distance of the test from the nearest wall to the cone diameter where S is the distance to the container wall and B is the diameter of the cone affects Q_c, the tip resistance. Q_c increased about 35% for the ratio S/B=2 compared to the ratio S/B=33. To achieve unbiased results the cone diameter B should be at least twenty times greater than the mean particle diameter D_{50} (Gui et al, 1998).

Test Program

The tests were performed at 50g with dynamic loading simulated by the Stored Angular Momentum (SAM) earthquake actuator, which uses energy stored in a flywheel to generate lateral shaking. The flywheel drives a reciprocating rod that is grabbed by a clutch to initiate an earthquake event. The SAM shaker has the capability to simulate earthquake motions of varying magnitude, frequency and duration. The SAM actuator allows sinusoidal earthquakes to be fired with strength, frequency and duration of choice at g-levels of up to 100g and a choice of a single frequency, or a swept-sine wave capability to investigate the natural frequencies of geotechnical models. The features of the SAM actuator are outlined by Madabhushi et al, (1998).

The miniature CPT device has a 6mm diameter rod fitted with a 60° conical tip connected to the piston of the cylinder. A load cell is placed at the top of the rod to measure the total force. The hydraulic cylinder has 200mm penetration distance and the valves were set so that the penetration rate is 2mm/s. Four bar pressure is applied to hold them up at high g and seven bar applied on top leaving three bar to penetrate each CPT at 50g. The experimental procedure is to perform two CPTs in flight at known distance from the end-walls at the same penetration rate before the earthquake load. Then, an earthquake is simulated and the CPTs are repeated at two other locations. This is summarized in Fig.1. In-flight CPT tests were performed on six models with six cone penetrations per model and located about 100mm from each other. Four before the earthquake and two after the earthquake. The heights of the sand models in the tests were 178 and 217mms for saturated and dry models respectively. The ratio between cone diameter and the average grain size D_{50} was 50. The properties of the LB100/170 sand used in the tests are summarized in Table 1. The test specifications with respect to test number, model type and relative density are given in Table 2. Centrifuge experiments discussed in this paper are from in-flight CPT soundings on several dry or saturated sand models with different relative densities. The models were prepared by using a sand hopper and the saturation was done under vacuum using silicone oil.

Table 1. Summary of basic properties of LB100/170 Sand.

Median Grain Size, D_{50}	0.120mm
Effective Grain Size, D_{10}	0.067mm
Specific Gravity, G_s	2.65
Minimum void ratio, e_{min}	0.502
Maximum void ratio, e_{max}	1.060

Dry and saturated sand tests were conducted with various instrumentation layouts. Instruments used in these tests were accelerometers and in saturated models pore pressure transducers. The earthquakes had a 50Hz peak frequency and to show the characteristics of the earthquake, the input motion is shown in Fig. 3 along with the pore pressure information received near this point. The accelerometer was placed at the bottom of the model at the center. The uniformity of horizontal motion across the soil column and the container verifies the unison in movement of soil and the container during base shaking. To measure uniformity accelerometers were attached to the individual rings of the ESB model container and at corresponding depths near the center and corners of the soil profile. Acceleration histories for container wall and the middle of the model showed identical traces indicating that the soil in the middle and the container is moving together. Attenuation of peak accelerations towards the end-wall was observed whereas the accelerations at the center of the box and on the container wall were similar. To investigate this behaviour further miniature CPTs were conducted.

Table 2. Test specifications.

Experiment no.	Model Type	ID(%)
BT-5	Dry	51.97
BT-6	Saturated	53.76
BT-7	Saturated	82.44
BT-8	Dry	73.48
BT-9	Dry	48.39
BT-10	Saturated	50.18

The CPT and its gantry can be seen in Fig.2 in their second positions before the earthquake loading is applied. Also in the figure the model is seen in the ESB container and the cylinders with 200m travel pistons inside them and the valves to control the penetration rate are shown.

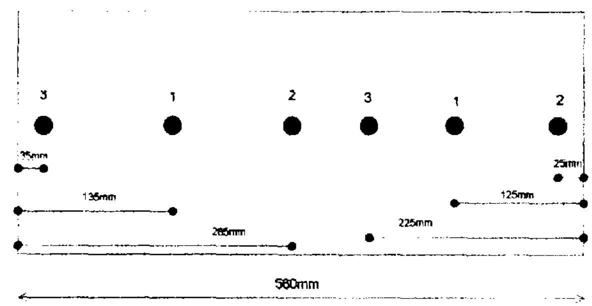

Fig. 1 Places of CPT tests done. Number one and two are executed before the earthquake and number three penetrations after the earthquake.

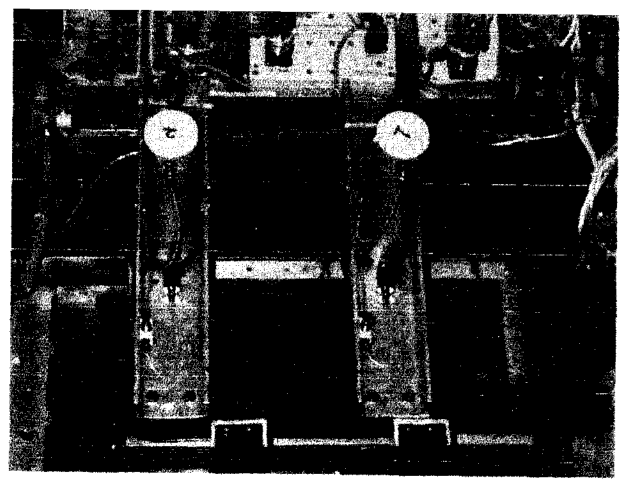

Fig. 2 Assembly of centrifuge package and the CPTs.

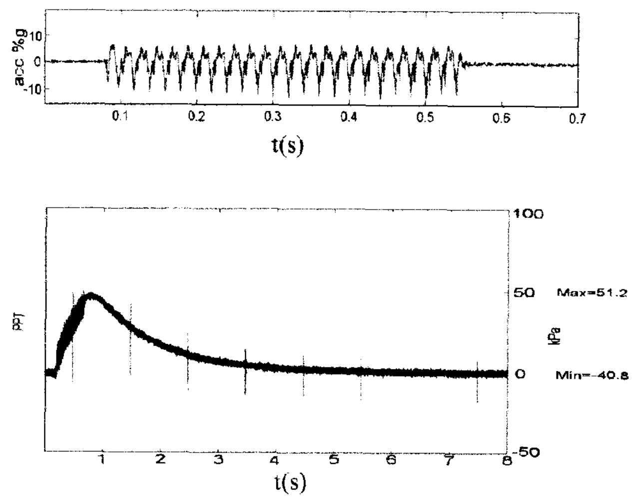

Fig.3. Input signal from a saturated sand model and the pore pressure dissipation observed near this point.

Uniformity of Soil Samples in the Centrifuge Model

Saturated Sand Layer. In Fig.4 penetration resistance acquired at various locations in a saturated model before the earthquake is plotted. The results shown on the following figures are not normalized resistances with vertical effective stress and all results are at model scale. The graph shows vertical effective stress against total penetration resistance observed. The results shown are for a saturated loose model for pushes at 135mm and 25mm from the end-wall and at the center of the model. The CPT at the center was pushed in to a greater depth, thus giving a higher peak penetration resistance. In this plot the penetration resistances have very similar curves confirming the model to be uniform. As can be seen in Fig.4, the boundary had little effect on the penetration resistance prior to the earthquake loading.

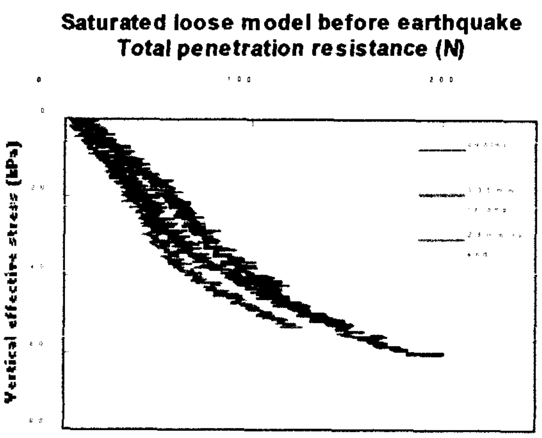

Fig. 4. Penetration resistances before the earthquake in saturated loose sand model.

Dry Sand Layer. In Fig. 5 penetration resistance acquired at 125 and 135mm from the end-walls for a dry loose model is shown. This shows the uniformity of the model before the earthquake. The plots show a fall in resistance at about 50kPa vertical effective stress, the zone in the middle is the zone where sand pluviation was stopped to place the instruments in the middle sand layer of the model. CPT measurements clearly pick up this region.

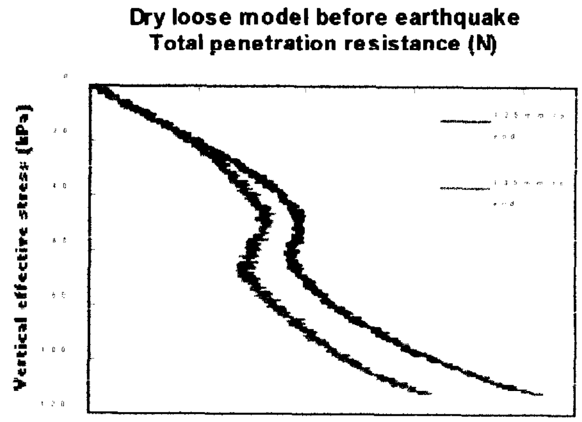

Fig.5. Penetration resistances before the earthquake in dry loose sand model.

Earthquake Effects on the Soil Models

Penetration Resistance in Dry Soil Models. In Fig. 6, results of penetration tests on a dry loose model with I_D=48% before the earthquake motion is shown. The center and the end-wall resistance are plotted on the same graph to compare them. As before, total penetration resistance is plotted against vertical effective stress. In Fig. 7, results of penetration tests on a dry loose sand model after the earthquake are shown. The CPTs were pushed before the earthquake at the center and near the end-wall. However the CPT near the end-wall was only penetrated to a depth corresponding to 70kPa vertical effective stress. From Fig. 6, we can see that the peak penetration resistance at 70kPa vertical effective stress was 408N both at the center and near the end-wall. Therefore we can conclude that before the earthquake the resistance at the center is similar to the resistance at the end-wall at comparable effective stress. An earthquake of magnitude 10% was applied and following that the CPTs were repeated. These results are presented in Fig.7. It can be seen from this figure that the penetration resistance at the center differ from that near the end wall after the earthquake. For example, at 70kPa vertical effective stress, the penetration resistance at the center was 440N. Earthquake loading clearly caused an increase in penetration resistance at the center. On the other hand the penetration resistance has dropped near the end wall. At 70 kPa, this value was only 250 N which is 40% smaller than the value prior to the earthquake (408 N).

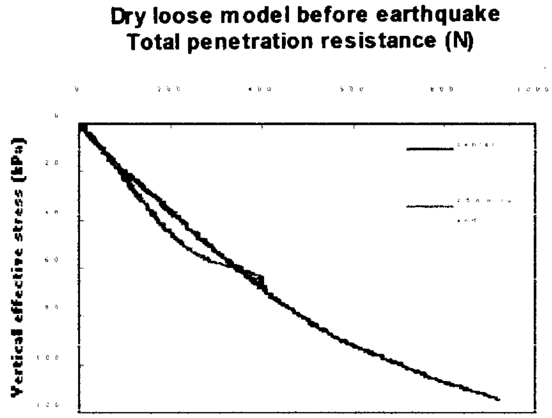

Fig.6. Penetration resistances before the earthquake in dry loose sand model.

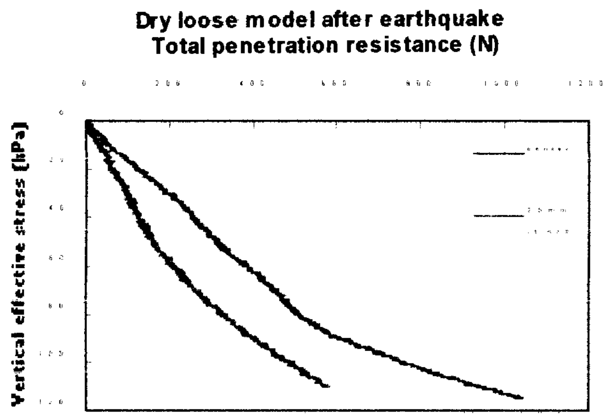

Fig.7. Penetration resistances after the earthquake in dry loose sand model.

Penetration Resistance in Saturated Soil Models. In Fig.8, the results of a penetration test on a saturated loose sand model with a relative density of I_D=54% before the earthquake are shown. The plots of center and end resistances are similar up to 50kPa, but after this depth, the end-value starts to increase with a different slope. In the case of saturated models, the effective stress is much smaller, there by reducing the arching effect near the boundary during swing-up. Due to the lower effective stress the CPT resistance is more or less same throughout the saturated model especially at shallow depths as seen in Fig.8. An earthquake of magnitude 10% was applied and following that the CPTs were repeated. In Fig.9 the results for the same model after the earthquake are shown. After the earthquake the difference between sites gets even smaller up to a depth where the effective stress is about 60 kPa. The resistance at the end and the center starts to deviate at 60kPa vertical effective stress. Up to that depth the soil layer became uniform as the arching effect observed before the earthquake has been destroyed. Beyond this effective stress (i.e. at greater depths) the effect of shear stresses due to arching on penetration resistance is seen. The earthquake loading clearly caused an increase in penetration resistance at the center, by about 30% while near the end wall the penetration resistance has dropped by 11%.

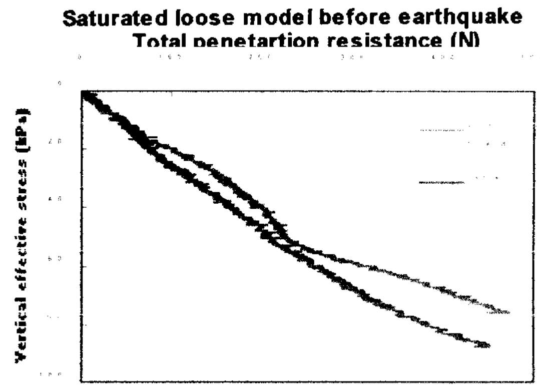

Fig.8. Penetration resistances before the earthquake in saturated sand model.

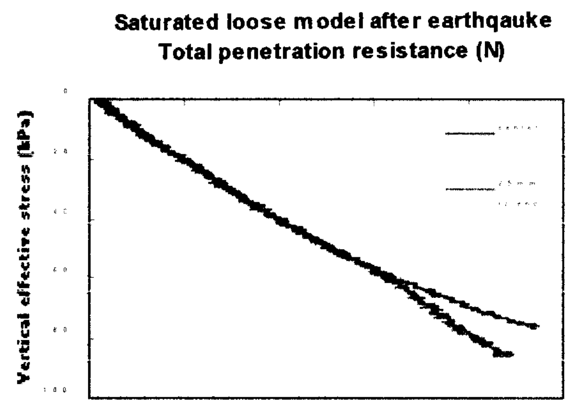

Fig.9. Penetration resistances after the earthquake saturated sand model.

When dry and saturated, loose and dense sand models behaviour before and after the earthquake are compared, the center of the model densifies relative to the boundaries. All results show the resistance at the center to be more than the resistance at the end-walls. The reason for this behavior may be that the soil layer does not have the same settlement as the end wall and the rought boundary would be holding the sand up causing boundary effects to be observed. If boundary effects are significant, densification of sand near the end walls during dynamic loading will be impeded because of arching and shear transfer to the walls. This is clearly seen in these results for dry and saturated models.

DISCUSSION

The results from the above experiments show that there is a difference in the soil stiffness before and after the earthquake loading due to the presence of rough shear sheets placed at the end walls. The concept of shear sheets was developed with the view of generating complementary shear stresses being generated at the boundaries in sympathy with the lateral shaking at the base, there by avoiding any dynamic moment being generated about the centroid of the soil model, Madabhushi et al (1995). These sheets are clearly meant to work during the earthquake loading. The results from the current study show the effects of the complementary shear sheets prior to and after the earthquake loading. Clearly the rough sheets at the end walls are providing arching in the soil following earthquake loading, when rest of the soil samples undergoes settlement.

This presents us with a different (and difficult) problem where we need rough sheets near the boundary during shaking, but a smoother boundary before and after the earthquake loading so as to minimise the development of any arching in soil which wishes to undergo settlement.

CONCLUSIONS

In this paper, we have discussed recent experiments which are important for quantifying the effectiveness of the ESB model container. It is also important for the optimization of the instrument layout into areas where the boundary effects are not significant. The results from these experiments are important to simulate dry and saturated soil in the field. For the former it is important because of the settlement characteristics of loose, dry sediments and for the latter to quantify liquefaction phenomena for soils that are below ground water level. Settlements can have a significant effect on the performance of structures during earthquakes. The results show the uniformity of the soil model prior to earthquake loading, and the penetration resistance changes after earthquake loading. The differences occurring before and after the earthquake between the center and end of the model were evaluated by measuring the total force required to push a 6mm diameter rod with a 60° conical tip at various locations at 50g. In case of loose saturated and dry models, more densification occurred at the middle of the model relative to the boundary region.

CPT profiles assist in the assessing the boundary effects of the ESB model container. Due to the stiffness of the wall not matching the soil and also differential vertical settlements between the soil and the wall, shear stresses are produced. These shear stresses decrease the total penetration resistance measured by the CPTs. This research has shown that CPT tests produce consistent and reliable data to interpret the influence of the boundaries. The results suggest that the complementary shear sheets cause differences in the soil behaviour between the center and the end-walls. Ongoing research will focus on the complementary shear stresses to quantify the zone of disturbed soil where arching is occurring.

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