# Dynamic soil container and sand pluviator for 1g seismic load tests on anchored retaining wall

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ABSTRACT: In this article the design and setup of the experimental facilities for 1g physical modelling of the seismic behaviour of multi-anchored retaining walls with a one dimensional shaking is addressed. The retained soil will be sand. The facility is composed by an already existing shaking table, a flexible container, a translational sand pluviator and the control and instrumentation hardware. The multiple design criteria that justified the adoption of an Equivalent Shear Beam type for the soil model container are introduced and discussed. The new sand pluviator will allow the preparation of homogenous soil deposits in horizontal directions with relative densities between 70% and 85%, a minor density variation in the vertical direction. The dynamic characteristics of the container and of the container with the model in were studied by a Rayleigh vibration analysis. Finally, the instrumentation setup is described with some detail.

## 1 INTRODUCTION

The behaviour of an anchored retaining wall during earthquake loading is a complex soil-structure dynamic interaction problem. In an ongoing research project on seismic behaviour of multi-anchored retaining walls the problem is being addressed by both numerical and physical modelling. The paper addresses the overall setup of the physical model test system. The designs of the container and of the sand pluviator are presented with some detail. The validation of the design was sought through numerical modelling of the soil-container interaction behaviour.

Although numerical models may be economic to develop when compared to physical models, there are still too many simplifications involved. Reduced-scale model tests are essential to study soil-structure interaction during earthquakes.

A physical model of the retaining wall is being prepared with a dry sand deposit inside a new specially designed container. The soil deposit will be produced with a new travelling pluviator. The physical model will be tested on an existing unidirectional shaking table at LNEC.

A FLAC finite difference numerical model was prepared to be calibrated against the physical model results. It is envisaged to perform economic parametric studies involving the geometry of the wall and of the retaining anchors, the frequency content of the base acceleration, the soil density and peak acceleration. A simpler approach by vibration analysis of a one generalized degree of freedom with the Rayleigh allowed a expedite estimation of the dynamic characteristics of the container filled with sand.

## 2 1G SEISMIC TESTING

The tests will be carried out with the LNEC unidirectional shaking table (Figure 1). The seismic horizontal platform consists of a large metal frame, to support the vibrating table and the hydraulic actuator. The vibrating table slides on upper and lower bearings chain which also absorb the moments and lock the table sideways. The vibrating table has dimensions wheelbase of 3.0 m × 2.0 m, with a rectangular fixing holes pattern of 1.0 m × 0.5 m. Its total weight is 30 kN, while the payload test is 60 N, limited by the capacity of the bearings.

## 3 TWO FUNDAMENTAL ISSUES

The fundamental problem with 1g physical models of seismic behaviour of structures is to guarantee the correspondence between the model and the prototype. In the case of geotechnical structures, an additional issue related with the presence of a container must be addressed.

The ideal container is one which gives a seismic response of the soil model identical to that obtained in the prototype, i.e. the semi-infinite soil layer 1D response under vertically propagating shear waves.

Figure 1. Overview of the shaking platform and its unidirectional hydraulic actuator.

The boundary conditions created by the model container walls have to be considered carefully, otherwise the field conditions cannot be simulated properly. The presence of rigid and smooth end walls in the case of a ground model introduce three serious boundary effects compared with a semi-infinite soil layer in the prototype (Dar, 1993):

1. Deformation incompatibility (Figure 2a) resulting in strain non-uniformity in the ground model. The deformation response of the ground model near the rigid end walls under horizontal one directional shaking is restricted to move together with the rigid end walls whereas in the uniform soil layer seismic response to vertically propagating SV waves all vertical planes undergo the same shear.
2. Stress dissimilarity (Figure 2b) arising from the fact that the smooth end walls of the ground container with smooth end walls cannot sustain the shear stresses.
3. Input excitation pattern dissimilarity since that of the prototype soil layer is dominated by energy of the vertically propagating shear waves, whereas, the same does not apply to the model due to the wave reflections from the rigid walls of the container.

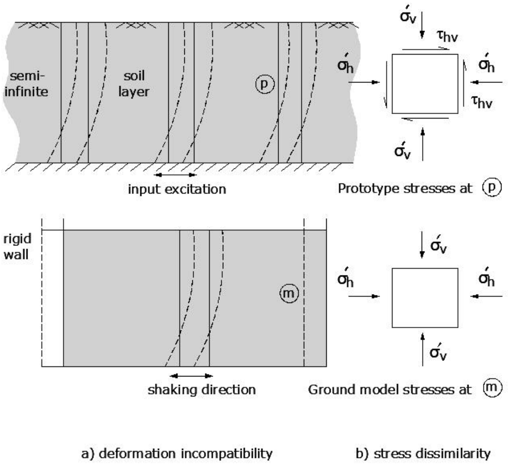

Figure 2. Effects of rigid boundary end walls (Dar, 1993).

Thus, one of the main aspects to address when implementing geotechnical dynamic physical models is the dynamic behaviour of the container.

An additional requirement is that the depth variation of properties of the soil in the container follows as close as possible the presumed variation in situ. Moreover, the soil density should be invariant in every horizontal plane.

## 4 THE FLEXIBLE CONTAINER

### 4.1 *Design criterion*

Several containers have been used throughout the last two decades (Teymur 2002), e.g. rigid containers, rigid containers with absorbing boundaries, stack ring apparatus at MIT (Whitman 1984), laminar model containers (Hushmand et al. 1988) and equivalent shear beam (ESB) containers (Schofield & Zeng 1992).

Zeng & Schofield (1996) defined several criteria to achieve similarity between model and semi-infinite soil layer 1D responses: (i) strain similarity, (ii) minimization of P waves generated at the end walls, (iii) stress similarity and (iv) no shear stresses induced between the side walls and soil during base shaking, to create the same two-dimensional condition as in the prototype. Those authors recognize that the first requirement is the most difficult to satisfy, since the stiffness of soil is likely to change under cyclic loading. They suggest designing end walls that match the dynamic properties of the soil deposit over working conditions, i.e. for an intermediate range of shear strain.

As for the present project, the concept of the ESB model container of Zeng & Schofield (1996) was adopted. Although the final subject of the test program is the seismic response of multi-anchored retaining walls, it was designed to simulate one-dimensional response of a semi-infinite soil layer.

Following Zeng & Schofield (1996), multiple design criteria were considered for the design of the flexible container, namely those related with the reproduction of a $K_0$ condition, the deflection pattern, the stress boundary conditions at the end and lateral walls and the dynamic behaviour.

### 4.2 *Deflection pattern*

A flexible shear-stack of alternating aluminum frames and rubber-like, elastomeric, sheets was designed so as to replicate the deflection pattern of the soil deposit, i.e. that of a shear beam. The elastomeric sheets are placed longitudinally only. Therefore a gap will exist between the aluminum elements at the end walls. The spillage of the soil through these gaps is prevented by an aluminum sheet as described in the sequence.

Following Zeng & Schofield (1996) the design criterion is that the deformation of each block of a rubber plus an aluminum frame will equal the deflection of the soil at an elevation between the top and bottom of the block. The longitudinal shearing is thus permitted and uncontrolled deformation avoided. A vertical offset was introduced between the longitudinal and transversal elements of the frames, so that the relative motion in the transversal direction is barred. This lateral restraint effect is additionally caused by four reinforcing lateral columns with only a minor gap to the container (Figure 3).

Teflon elements will be placed over the contact surface of lateral columns.

The container is 2.00 m long by 0.75 m wide and 1.75 m high (Figure 3). The aluminum frames section is a hollow square 85 mm wide and 2 mm thick, whereas the rubber strips have rectangular cross section 80 mm wide and 30 mm thick.

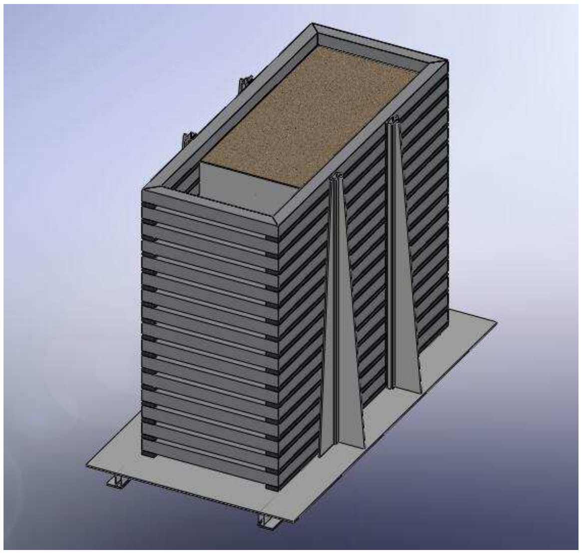

Figure 3. Schematic view of the container.

The mechanical properties of the elastomeric material were determined by oscillating shear ring tests and slow cyclic linear direct shear tests. Figure 4 show the shear strain-shear stress hysteresis loop and the vertical strain versus shear strain curve of a sample tested under a confining vertical stress of 20 kPa. A corresponding shear modulus of 0.1 MPa and a dilatancy angle of 2.5º were obtained.

## 4.3 *Reproduction of the $K_0$ condition*

The aluminum bars were designed to guarantee design to $K_0$ condition reproduction at the worst case scenario of the shear-stack full of dry sand. A maximum lateral deflection of 1 mm at the lateral walls was allowed with no consideration of the restraining effect of the four vertical beams at the lateral faces.

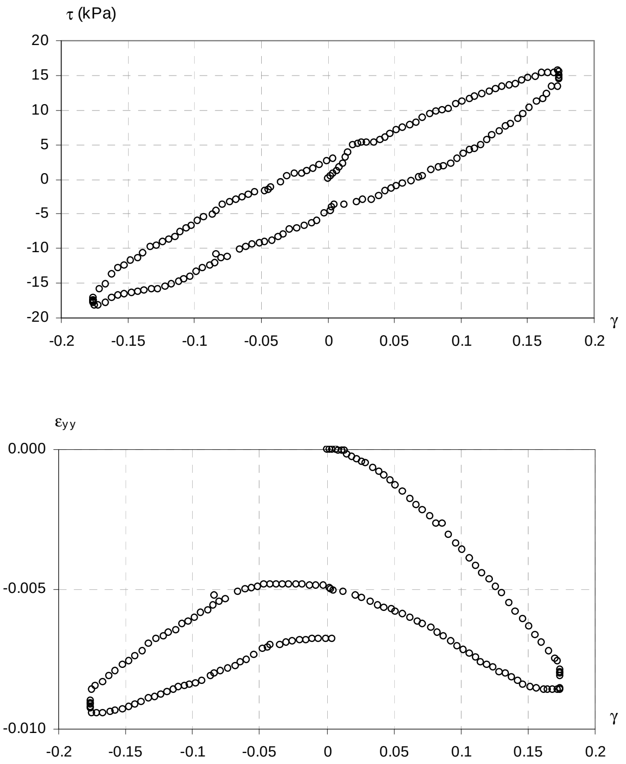

Figure 4. Elastomeric material test results at vertical stress of 20 kPa (a) shear strain versus shear stress; b) vertical strain versus shear strain).

## 4.4 *Dynamic behaviour*

The dynamic behaviour criterion by Zeng & Schofield (1996), i.e. that during base shaking the end walls should have the same deflection and natural frequency as the soil layer in the model container, was slightly improved. In the present design it was considered that the boundary effects would be minimized if the dynamic response of an idealized soil layer with the internal dimensions of the container matched that of the soil model, i.e. the joint response of the soil and the container. This differs, as well, from the adopted criterion by Dar (1993) that the flexible stack fundamental frequency should match the natural frequency of the soil deposit at a strain level close to failure. According to Dar, by this way, the soil deposit would drive the stack and not otherwise.

Following Zeng & Schofield (1996) ESB approach, the base and end walls of the container will be covered by a thin sheet of aluminum glued to the base of the container and covered with a slim layer of glued coarse sand all over its internal face, i.e. at the base and at the end walls.

The inner face of the lateral walls will be smoothened by using a thin rubber membrane with greased contact to the container to prevent shear stresses development.

The base plate comprises a 10 mm steel plate reinforced underneath by a number of welded longitudinal and transversal members. These provide fixing of the container to the shaking table. Two design loads were considered: the shaking load and the carrying load.

The dynamic load was estimated from the maximum load capability of the shaking table and the combined weight of the soil sample and container. This load was applied as a horizontal force and the total weight as a vertical force both at the centre of mass with horizontal reactions at the fixing holes and vertical support at the underneath surfaces of the reinforcing members. A peak value of 25 MPa for the von Mises equivalent stress was obtained with a FEM commercial software, well below the acceptable limit for any typical structural carbon steel.

The carrying load was actually a more severe load case, since supporting the weight underneath was not considered to be viable. This design situation overcomes largely that of the horizontal base excitation. The weight had to be supported by four hinges where the hoisting cables will fit. In this case, the peak equivalent stress was found to be 173 MPa which required some care with the steel grade choice. A deformation check was also performed, the maximum deformation estimative being well below 1 mm.

For easy emptying of the soil after each test, a hole with a sliding gate was provided at the centre of the base plate. Figure 5 shows a schematic longitudinal section view with anchored flexible wall on position.

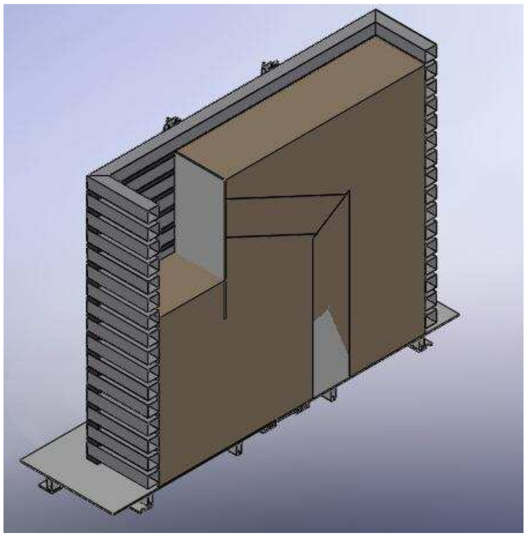

Figure 5. Schematic longitudinal section view of the container with anchored flexible wall on position.

## 5 CONTAINER AND MODEL EIGENFREQUENCIES

The soil deposit will be made of the SP-49 sand, a commercial sand from Sibelco which physical properties are summarized in Table1 (Bilé Serra 1998).

Table 1. Physical properties of SP-49 sand

| Property | |
|---|---|
| Uniformity coefficient, Cu | 1.3 |
| Curvature coefficient, Cc | 0.9 |
| Particle unit mass, G | 2.65 |
| Maximum dry unit weight, $\gamma_d^{max}$ | 17.15 kN/m$^3$ |
| Minimum dry unit weight, $\gamma_d^{min}$ | 13.76 kN/m$^3$ |
| Minimum void ratio, $e_{min}$ | 0.516 |
| Maximum void ratio, $e_{max}$ | 0.889 |

An extensive laboratory test program to determine the strength characteristics and shear modulus and damping ratio dependence on shear strain at low stress level is presently under way. Therefore, the preliminary calculations for the container design were performed with parameters from previous research work and literature equations. The Equation 1 by Hardin & Richart (1963)

$$G_0 = 3230 \frac{(2.97 - e)^2}{1 + e} \sqrt{\sigma'_0} \qquad (1)$$

where e=void ratio and $\sigma'_0$=effective mean stress, was used to estimate the small strain elastic shear modulus $G_0$.

A generalized one degree of freedom model was used to characterize the container dynamic properties. The fundamental eigenfrequencies under working conditions of (i) the container (5.1 Hz), (ii) the soil deposit (14.9 Hz) and (iii) the container filled with sand (13.9 Hz) were estimated by a vibration analysis with the Rayleigh method.

## 6 SAND PLUVIATIOR

LNEC has some experience in design and production of pluviators to reconstitute granular soil models. In the past, two types of air pluviation devices were produced. One is a vertically travelling pluviator to prepare samples for triaxial test and hollow samples for torsional shear tests, up to 0.5 dm$^3$ (Bilé Serra et. al. 1997 and Madeira & Emílio 1997). The second is a horizontally travelling pluviator for preparation of sand deposits for centrifuge testing with variable drop height, up to 55 dm$^3$ (Portugal 1999).

A new pluviator was designed to prepare dry sand deposits with relative density between 70 and 85% with variable fall height always larger than the critical height. As the critical height depends on the adopted combination of pluviation setup and sand, it will be determined experimentally prior to the soil deposit preparation.

The design was optimized relative to the key parameters (Vaid & Negussey 1984 and Passalacqua 1991), i.e. drop height, flow rate and translation speed of the spreader. The new sand pluviator will consist of a steel frame and a small container travelling on two rails at the top of the frame, moved by a worm gear motor driven by an electronic speed controller (Figure 6).

The small container will be filled at a parking position below a main sand container. This will be filled from 500 kg sand bags raised up to the pouring position by a roller bridge (Figure 7).

Figure 6. Schematic view of the pluviation equipment setup.

Two electrical limit switches on the rails will limit the path of the travelling container. A lower rectangular gate will control the sand flow into the model container. A technician on a platform at the main structure commands the pouring operation to the model container.

The new travelling sand pluviator will have a maximum drop height (to ground) of 2.76 m, a deposition area of 0.77x2.20 $m^2$, a maximum flow rate of 586 g/s (adjustable by positioning the gate), a translation speed between 2 and 14 cm/s. The main container volume is 363 $dm^3$, whereas the small container volume is 77 $dm^3$.

The construction is now underway. A set of calibration tests will follow, prior to the effective usage of the system for model preparation.

During the container filling, the sand relative density will be checked by small volume recipients placed over some of the soil layers during pluviation, which are collected for weighting.

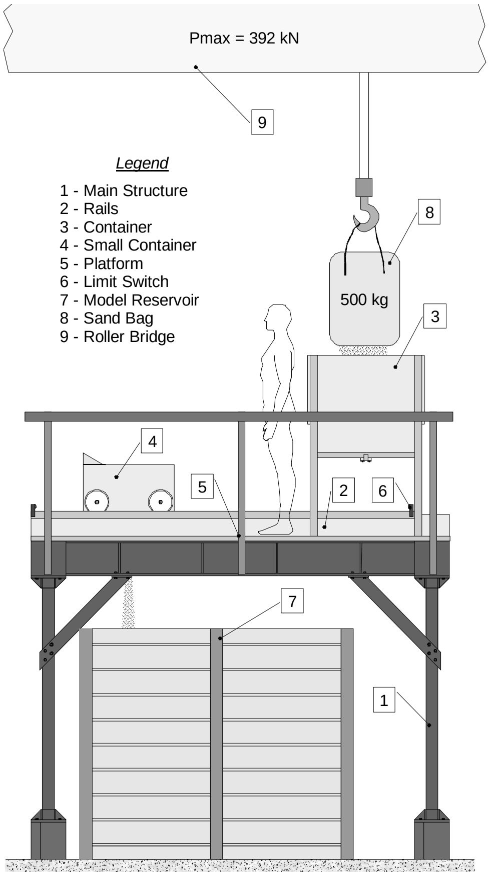

Figure 7. Side view of the sand filling equipment.

## 7 INSTRUMENTATION

To understand the key aspects of a multi-anchored model, the instrumentation setup is composed by several devices at optimized positions so as to capture the most relevant model features. The variables to be measured are the following: (i) shaking table longitudinal displacement and triaxial acceleration, (ii) displacement vectors of the wall face, (iii) acceleration of the wall, (iv) displacements and accelerations of the flexible container, (v) extensions at both external and internal surfaces of the wall, (vi) axial extension of the anchors, (vii) triaxial acceleration at the surface and inside the soil deposit, (viii) deformed shape of initially vertical alignment at the end of shaking and (ix) soil settlement or heave both at the surface and in the interior.

Inductive and 2D (i.e. a Hamatsu system) and 3D (i.e. a Krypton measuring system) optical displacement transducers will be used to measure displacements. The later will used to measure the displacements at the wall face at different elevations (Figure 8). The LEDs will be attached directly to the wall surface.

A video camera located will be used to record the horizontal displacement time history of the front face top during shaking.

Anchor forces and flexural moments of the wall will be evaluated from the readings of extensometers placed on both sides of the wall in opposite positions and defining two vertical reading alignments.

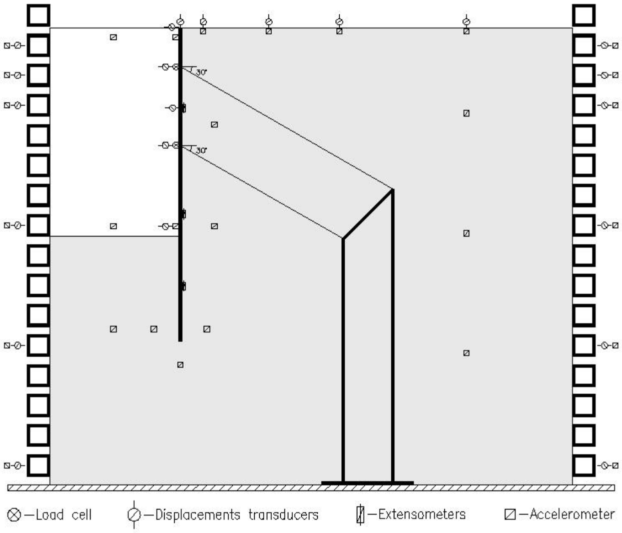

Figure 8. Localization of instrumentation devices.

Final horizontal displacements inside the backfill are measured from the position of very thin and flexible PVC pipes. These are held in position during the sand pluviation by stiff reinforcements, which are removed prior to shaking.

At the end of a test, and before dismantling the soil deposit and wall the pipe is grouted with epoxy to allow measuring the deformed shape, which is deemed to reflect the surrounding soil deformation.

A LNEC proprietary software package (Mendes & Costa 2007) will be used both for data acquisition and signal processing and analysis of tests results.

## 8 CONCLUSIONS

An ongoing research project at LNEC aimed at investigating the seismic response of multi-anchored retaining walls was introduced in this paper. The experimental setup for 1g shaking table physical modelling of such retaining systems was described. A new travelling sand pluviator to prepare homogeneous soil deposits inside a new container was introduced.

The container design philosophy is that of the ESB container by Schofield and Zeng aiming at reproducing the deflection pattern and the dynamic characteristics of the one directional soil response under vertically propagating shear waves. A design criterion based on the fundamental eigen frequency distance between soil deposit and the container filled with soil was adopted. Future results will be made available and published in the near future.

## ACKNOWLEDGMENTS

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