Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0786

XVII European Conference
ECSMGE 2019 Reykjavik
on Soil Mechanics
and Geotechnical Engineering

A new shaking table apparatus for large scale physical modelling of geotechnical systems

Un nouvel appareil à table vibrante pour la modélisation physique à grande échelle de systèmes géotechniques

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ABSTRACT: A new shaking table apparatus with a large laminar box has been set up in the laboratory EUROLAB-CERISI of the University of Messina. The apparatus consists of a shaking table connected to a servo-hydraulic actuator, a large shear stack container for the soil and an automated system for soil deposition. The actuator can excite the low friction shaking table, supporting a maximum load of about 32 t, by applying horizontal displacements in the range ± 255 mm and is capable of reproducing a wide set of real and artificial seismic motions. A large laminar shear box has been assembled and a hopper can be moved back and forth above the shear box allowing sand pluvial deposition. The velocity of the hopper, the width of its lower opening and the soil falling height can be adjusted to attain the desired relative density of the soil model.The paper provides details of this new experimental facility and describes the results of preliminary dynamic tests, aimed to characterize the performance of the whole equipment.

RÉSUMÉ: Un nouvel simulateur de séisme a été mis en place dans le laboratoire EUROLAB-CERISI de l'Université de Messine. L'appareil consiste en une table vibrante reliée à un actionneur servo-hydraulique, une grande boîte laminaire et à un système automatisé pour le dépôt du sol. L'actionneur peut exciter la table, supportant une charge maximale d'environ 32 t, en appliquant des déplacements horizontaux dans la plage de +/- 255 mm et est capable de reproduire un large ensemble de mouvements sismiques réels et artificiels. Une grande boîte a été assemblée et une trémie peut être déplacée d'avant en arrière au-dessus de la boîte, permettant ainsi un dépôt pluvial en sable. La vitesse de la trémie, la largeur de son ouverture inférieure et la hauteur de chute du sol peuvent être ajustés pour atteindre la densité relative souhaitée du modèle de sol. Le travail présenté fournit des détails sur cette nouvelle installation expérimentale et décrit les résultats d'essais dynamiques préliminaires visant à caractériser les performances de le simulateur de séisme.

Keywords: Shaking table, Laminar box, Physical modelling

1 INTRODUCTION

Physical modelling allows studying the response of complex geotechnical systems under laboratory-controlled conditions by simulating loading conditions that can hardly be monitored in real systems. Typically, seismic tests on scaled models are performed either under normal gravity conditions, using shaking tables, or under an augmented gravity field, in a centrifuge. Worldwide a number of shaking tables equipped with large laminar boxes are available; these allow overcoming some typical limitations of the conventional small soil containers, that are not suitable to satisfactorily reproduce the prototype field conditions.

Recently a new apparatus for seismic tests has been set up in the laboratory EUROLAB-CERISI of the University of Messina (Italy). It consists of a shaking table connected to a servo-hydraulic actuator, a large laminar box and a system for soil pluvial deposition.

The paper describes some of the main features of this experimental facility along with the results of some preliminary dynamic tests aimed to examine the capability of the servo-hydraulic control system to apply a prescribed acceleration time-history to the shaking table.

Further details about the whole apparatus are given by Bandini et al. (2019), together with the results of the static tests carried out to check that plane strain conditions are satisfied during the filling of the laminar box.

2 EXPERIMENTAL EQUIPMENT

A large single degree of freedom shaking table equipped with a large-scale laminar box for testing physical models of geotechnical systems under seismic loading conditions has been installed in the laboratory EUROLAB of the University of Messina.

A lateral and a plan view of the equipment are shown in Figure 1. The laminar box internal dimensions are: length L= 6 m, width W= 1.5 m and height H= 2 m; it consists of 18 aluminium rectangular hollow section rings, which are stacked alternately with EPDM rubber sections and polyzene sheets in the end and side walls of the box, respectively. The EPDM rubber elements and the polyzene sheets allow the container to deform under horizontal shaking according to a shear beam mode, reproducing as closely as possible, a free-field condition. As described by Bandini et al. (2019), static tests confirmed that the rings and their supporting system provide soil lateral confinement in order to reproduce zero lateral deformation conditions (k_0 conditions). Specifically, measured lateral displacement resulted more than one order of magnitude lower than the displacement required to attain the active limit state in sands.

The floor of the laminar box is covered with a sheet of abrasive paper to aid the transmission of shear waves; the internal end walls are similarly treated to enable generation of complementary shear stresses.

In order to minimize the friction between the internal side of the lateral walls and the soil specimen, the internal lateral walls are covered with two latex sheets lubricated with hexagonal boron nitride.

In Figure 2 a general view of the equipment (Fig. 2a) and some details of the features of the shaking table and of the laminar box are shown (Fig. 2b,c). Specifically, Figure 2b shows a detail of the end walls of the laminar box, where the aluminium bars and the EPDM elements can be distinguished, while Figure 2c shows a detail of the side walls, where a series of rollers in contact with the aluminium bars and green thin polyzene sheets between bars can be observed.

The laminar box is fixed to the table and is shaken horizontally by a servo-hydraulic actuator which operates in a displacement control mode with ±255 mm stroke and 32 tonnes of payload. Hydraulic power for the actuator is provided by three hydraulic pumps capable of delivering 1200 litre/min at a working pressure of 300 bar. Linear guideways consisting of sliding rails and bearing blocks are used to allow an almost frictionless horizontal movement without vertical motions.

A spreading system was designed for preparing the soil specimen inside the laminar box by the pluviation method. The spreader consists of a hopper (Fig. 2d), with an internal volume of 1.5 m^3, that can move back and forth above the soil container, driven by a stepper motor, and the direction of the motion is automatically reversed.

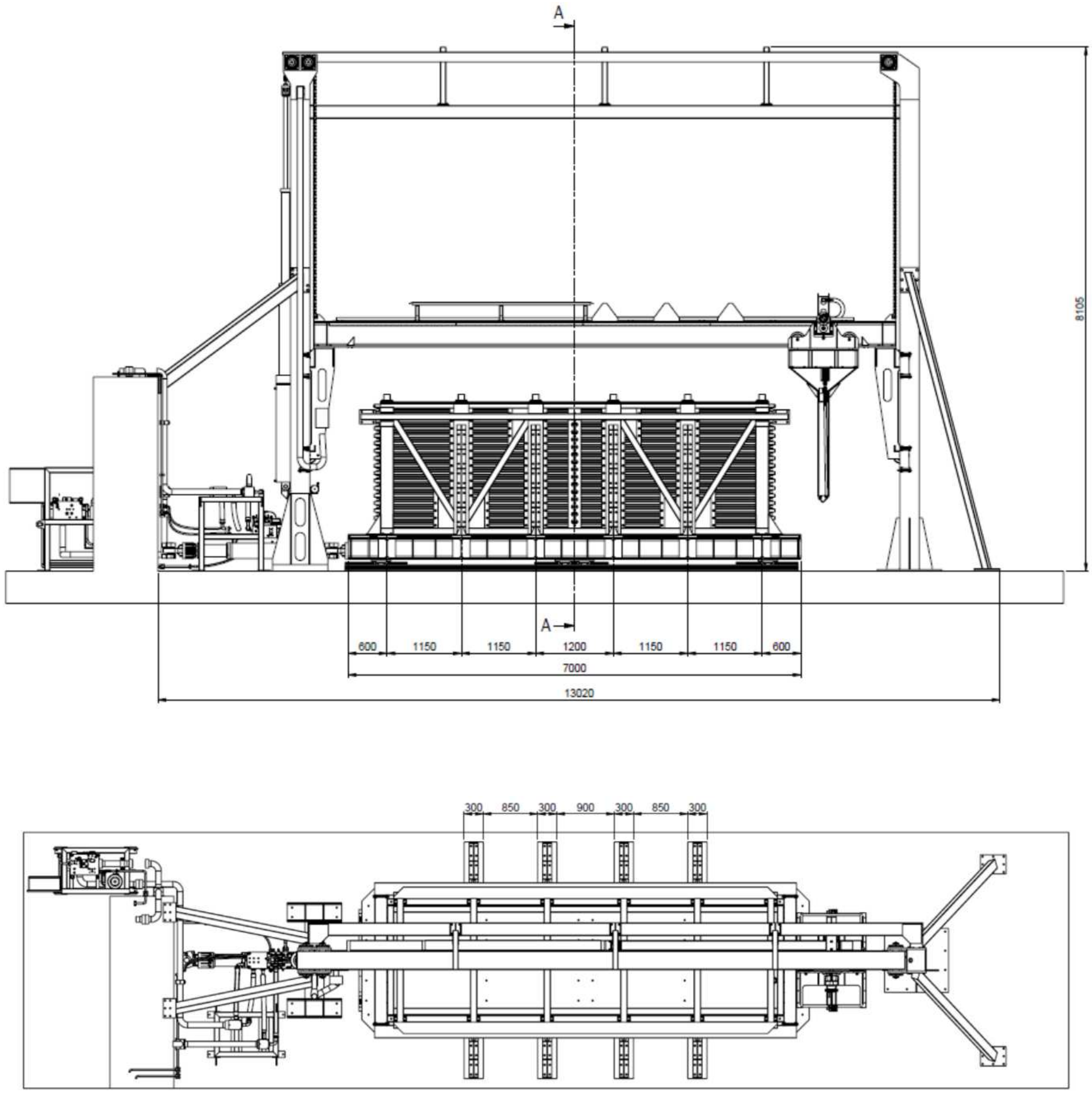

Figure1. Lateral and plan view of the EUROLAB equipment for shaking table tests on geotechnical systems.

The soil falls from a rectangular opening located at the bottom of the hopper (different opening width can be used during the test varying from 1to 15 mm) and the hopper can move at a constant velocity up to 10 cm/sec. The beam supporting the hopper can also move up and down allowing to adjust the drop height of soil particles in the range 30-3000 mm from the soil level inside the laminar box.

The capability of the described pluviation system to control the velocity of the hopper, its opening width and the drop height during the material deposition allows achieving a high degree of spatial uniformity both in terms of relative density and grain size distribution of the soil model.

3 DYNAMIC TESTS

A robust controller has been implemented to guide the table in following the prescribed motion, minimizing the effect of the specimen inside the laminar box.

A displacement feedback loop is used to control the motion of the table and force stabilization is provided by an additional actuator force feedback loop. Since the acceleration records to be applied to the table are usually broadband signals, the displacement control strategy has been enhanced with additional feedforward control signals in order to increase the fidelity in acceleration reproduction. The result is a tuned shaking table control system consisting in a total transfer function applied between the command and feedback signals.

Figure 2. a) General view of the equipment, b) rubber sections at the end walls of the laminar box, c) steel rollers and polyzene sheets (visible between aluminium rings) and d) the hopper during sand deposition.

As suggested by Luco et al. (2010), to account for possible dynamic interactions between the specimen and the table, the tuning process has been conducted with the laminar box full of dry sand.

The capability of the tuning process implemented in the control system was verified using a set of acceleration records, selected from ITACA and PEER databases (Luzi 2017; Ancheta et al 2013), for which Table 1 lists the moment magnitude M_w of the corresponding seismic event, the Joyner-Boore distance R_{JB} of the recording station, the peak acceleration a_{max}, the mean period T_m, the Arias intensity I_a and the number of equivalent loading cycles N_{eq} evaluated according to the procedure by Biondi et al. (2012). Data in Table 1 show that the considered accelerograms span over wide ranges of amplitude, frequency and energy content.

The accelerograms were double integrated to derive the displacement time-histories that were applied as command signals to the servo-hydraulic actuator system.

During the tests, an accelerometer of high output capacitance, operating over a frequency range of 0 - 3000 Hz, was used to record the acceleration of the table. To reduce noise, signals from the instrument were passed through a low pass Butterworth filter set to 100 Hz; data were acquired at a rate of 1000 Hz.

The acceleration time-histories recorded at the table were then compared to the target seismic acceleration records and the relative error ε_a on the peak acceleration, as well as the relative root mean square error ε on the 5% damping elastic response displacement (ε_{SD}) and acceleration spectrum (ε_{SA}) and on the Fourier amplitude spectrum (ε_F) were evaluated as:

$$\varepsilon_a = \frac{a_{ref} - a_m}{a_{ref}} \quad (1)$$

$$\varepsilon = \frac{\sqrt{\sum_{i=1}^{N}\left(x_{ref,i} - x_{m,i}\right)^2}}{\sqrt{\sum_{i=1}^{N}\left(x_{ref,i}\right)^2}} \quad (2)$$

In equation 1 a_{ref} is the peak acceleration of the target motion while a_m is the peak acceleration measured at the table; analogously, in equation 2 x_{ref} is the target spectral datum and x_m is the corresponding datum evaluated using the measured motion, while N is the number of datapoints describing a given period interval. The computed values of ε_a, ε_{SD}, ε_{SA} and ε_F are listed in Table 2.

Apart from a few cases, the relative error on peak acceleration is generally lower than 15%, the relative error on the displacement and acceleration spectra is generally less than 30%, while the relative error on the Fourier amplitude spectra is generally less than 50% and is affected by differences between measured and target motion at high frequencies.

Table 1. Characteristics of the acceleration time-histories used in the dynamic tests.

Earthquake	**Station – Orientation**	M_w	R_{JB} (km)	a_{max} (g)	T_m (s)	I_a (cm/s)	N_{eq}
Irpinia (1980)	Bisaccia – (North-South)	6.90	17.98	0.10	0.62	28.53	11.39
Kobe (1995)	Kobe University – (090)	6.90	0.92	0.31	0.38	81.73	5.90
Loma Prieta (1989)	Gilroy Array #1 – (090)	6.93	9.64	0.49	0.27	169.00	7.59
Northridge-01 (1994)	LA-WonderlandAve – (185)	6.69	20.29	0.16	0.26	20.40	8.02
San Fernando (1971)	Pasadena-Old Seismo Lab– (270)	6.61	21.50	0.21	0.24	34.21	9.02
Sicily (1990)	Sortino – (East-West)	5.60	24.58	0.11	0.15	5.52	5.33
Umbria Marche (1997)	Cesi Monte – (North-South)	5.60	6.20	0.18	0.18	11.41	4.74
Friuli (1976)	Tolmezzo – (East-West)	6.40	10.22	0.32	0.37	120.55	9.70

To get an overview of the performance of the "tuned" servo-hydraulic control system in terms of fidelity in signal reproduction, the target and the measured acceleration time-histories were compared for each test.

Figure 3 presents a comparison between the target and the measured data relative to the accelerograms of Kobe (Figs. 3a-e) and Loma Prieta (Figs. 3f-j). Specifically, the figures show the results relative to the acceleration (Figs. 3a and 3f), velocity (Figs. 3b and 3g) and displacement (Figs. 3c and 3h) time histories, the Arias Intensity (Figs. 3d and 3i) and the Fourier amplitude spectra (Figs. 3e and 3j). The target and the measured velocity time histories were obtained by integrating the target accelerogram and the acceleration time-history recorded at the shaking table, respectively, applying a cubic base line correction. The target displacement time histories represent those imposed as input to the shaking table, while the measured time histories were recorded by the actuator.

It can be observed that measured acceleration and velocity time-histories suitably reproduce the target real inputs but they also exhibit amplification phenomena (more evident for the Kobe record) especially in the strong motion interval (Figs. 3a,b and 3f,g). Figures 3c and 3h point out that the displacement time-histories were satisfactorily reproduced despite the displacement input was previously modulated in amplitude and phase by the applied transfer function to optimize the input accelerogram. In Figure 3d, relative to the case of Loma Prieta record, the Arias Intensity plots are almost perfectly matched, while in Figure 3i, relative to the Kobe record, they exhibit the same trend but the plot of I_a obtained from the measured acceleration is affected by the above mentioned amplification phenomena starting from about t=6 seconds. The Fourier amplitude spectra (Figs. 3e and 3j) show that the amplification phenomena can be mostly observed in the high frequency range, far from the principal frequency of the target record.

The plots in Figure 3 and data in Table 2 show that the features of the target accelerograms, in terms of amplitude, frequency and energy content are satisfactorily reproduced by the "tuned" servo-hydraulic control system.

Table 2. Comparison between target and measured acceleration time-histories: relative errors.

Record	ε_a	ε_{SD}	ε_{SA}	ε_F
Bisaccia	50%	14%	13%	38%
Kobe University	11%	9%	9%	30%
Gilroy Array #1	12%	13%	7%	24%
LA-Wonderland Ave	33%	22%	19%	43%
Pasadena-Old Seismo Lab	15%	28%	19%	42%
Sortino	9%	17%	21%	55%
Cesi Monte	35%	19%	39%	58%
Tolmezzo	12%	12%	11%	23%

4 CONCLUDING REMARKS

In this paper a description of the new equipment for dynamic physical modelling of geotechnical systems housed in the EUROLAB Laboratory of the University of Messina is provided, giving details of the geometry and the mechanical features of the shaking table, of the laminar box and of the soil deposition system.

Static tests described in a previous paper (Bandini et al., 2019) proved that plane strain conditions are verified with good accuracy. The dynamic tests demonstrated the capability of the shaking table to reproduce the desired acceleration input. Relative errors evaluated between measured and target motions for a set of accelerograms resulted reasonably acceptable since they are mostly affected by the equipment response at frequencies typically higher than the input motion frequency.

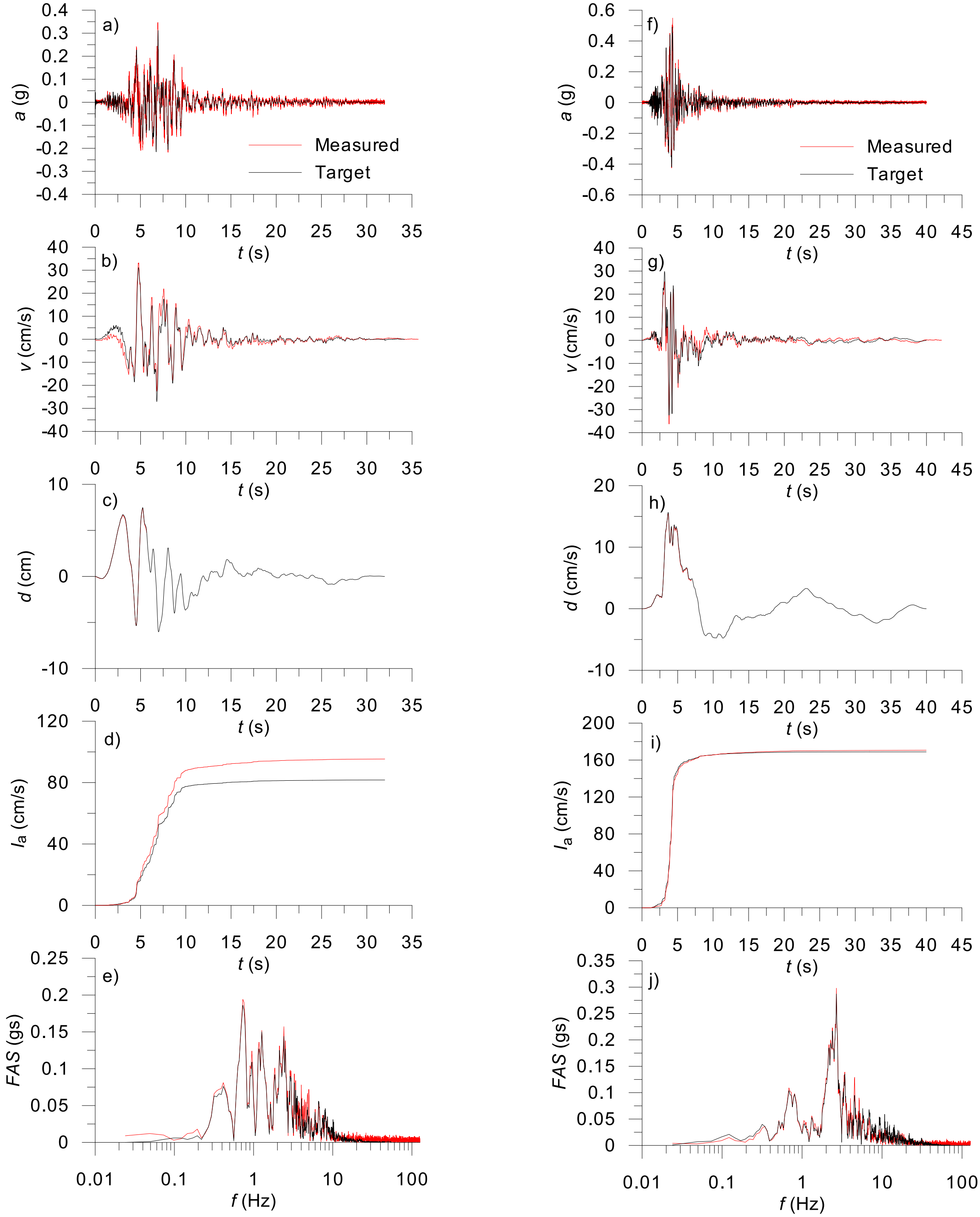

Figure 3. Comparison between target and measured motions for the case of the Kobe (a-e) and Loma Prieta (f-j) records: a,f) acceleration time-histories, b,g) velocity time-histories, c,h) displacement time-histories, d,i) Arias Intensity, e,j) Fourier amplitude spectra.

5 ACKNOWLEDGEMENTS

The equipment described in the paper is the result of an intense design and manufacturing activity carried out by Bosch Rexroth. The unvaluable contribution of A. Capuzzi, B. Fazzari, A. Stella, G. Ricucci, L. Soprano (Bosch-Rexroth) and of A. Palopoli (formerly Bosch Rexroth) is gratefully acknowledged.

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