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Experimental seismic analysis of geosynthetic-reinforced soil structures with three-dimensional reinforcements by shaking table tests

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ABSTRACT: The authors present the results of some tests performed on the shaking table of University of Catania. The tests, conducted with a model of geosynthetic-reinforced soil wall and slope, were subjected to a sinusoidal input and to the E-W component of the 1990 Catania earthquake. A polypropylene biaxial geogrid was used as soil reinforcement. A three-dimensional distribution was used inside the models. The soil used to design the models was a dry silica sand of the Sicily East Coast.

The results obtained, compared to similar tests conducted with a classical distribution of the reinforcements, showed a reduction in permanent displacements of the facing; the failure surface does not agree with that predicted by M&O. Reinforced structures showed a dynamic response as a function of their stiffness; the influence of frequency of the motion is evident and very high acceleration level was necessary to record damage to the model and to obtain an evident failure surface.

1 INTRODUCTION

An evaluation of the dynamic behaviour of geosynthetic-reinforced retaining structures could be made through the observation of the retaining-structure damage during the recent earthquakes. These structures performed well during the motion, with a reduction of permanent deformations and displacements.

Many authors have study the design problem finding various solutions, and a large contribution has come from experimental analysis. Juran and Christopher (1989) describes the results of a laboratory model on the performance, behaviour and failure mechanisms of reinforced soil-retaining walls using different materials. Law et al. (1992) performed a certain number of centrifuge tests to predict the response of a full-scale geosyntetic-reinforced wall.

Some full-scale test were performed to evaluate the performance of reinforced soil-wall with rigid facing, which showed that the wall responded well to severe earthquake, including foundation liquefaction (Murata et al., 1994). Shaking table tests were performed by Sugimoto et al. (1994). Michalowski (1997) have evaluated the reinforcement necessary to prevent slopes from collapsing due to reinforcement rupture, pullout or direct sliding, obtaining a design charts for the required strength and length of the reinformcement. The stability method based on the kinematic theorem of limit analysis was also used by Ausilio et al. (2000). Further experimental and numerical analysis were conducted on reinforced wall model by El-Emam, et al. (2001), Sofronie et al. (2001), Watanabe et al. (2001) and Hatami & Bathurst (2001). The model used for the tests carry out using the University of Catania shaking table, was calculated on the assumption of Jewell (1991) approach, as modified by Cascone, et al. (1995). All the tests presented in this paper form part of a large, experimental program conducted at University of Catania, with the purpose of investigating the dynamic behaviour of reinforced structures with various boundary and surcharge condition, seismic input and reinforcement distribution (Lo Grasso et al. 2004a, 2004b, 2005).

2 EXPERIMENTAL SET-UP AND SEISMIC INPUT

The shaking table device, available at the geotechnical laboratory of Catania University, is the same used and described by the authors in the previous tests conducted (Lo Grasso et al. 2004a and b, 2005). The geosynthetic-reinforced soil walls and slope used in the present test was designed with height h = 35 cm and h = 38 respectively. The soil used in all the tests is a dry silica sand from the east coast of Sicily whose characteristics are D_{60}/D_{10} = 2.407, D_{50} = 0.42 mm, maximum and minimum unit weight γ_{max} = 18.27 KN/m^3 and γ_{min} = 15.04 KN/m^3 respectively, and peak value of the shear strength φ = 37°. Backfill was prepared by dry pluviation, with which the deposition height was maintained constant respect the backfill, obtaining a final relative density Dr ≅ 75%.

A polypropylene biaxial geogrid was used with maximum strength on both longitudinal and transversal direction equal to 4.50 KN/m and 6.0 KN/m respectively.

The reinforcements were distributed over the height of the wall with a non-uniform distribution having a step of 0.05 m from the base to a height of 0.25 m and of 0.035 m until the top of the model. Two vertical reinforcements were introduced inside the model, from the base to the top to obtain a three-dimensional distribution.

The model facing was made by a certain number of aluminium L-shaped sections, connected by a metal hinge and placed into the test box along a vertical guide to support the construction of the model.

The reinforcements, were anchored to the vertical facing in the internal face of each aluminium element. A uniform surcharge, aimed at applying a surcharge value of 1 kPa, was used in some tests.

Figure 1 show a sequence of the construction phases of the model where it is possible to observe the horizontal and vertical placements of the reinforcements. The models were subjected to the same sinusoidal input of previous tests, where the frequency and amplitude was varied alternatively, and to the E-O component of the 1990 Catania earthquake.

3 EXPERIMENTAL RESULTS

The experimental program and displacements recorded, for the tests without surcharge, are given in Table 1. This table reports the characteristics of sinusoidal input in term of frequency and amplitude and the displacements recorded at the base and at the top of the wall. The last row shows the actual signal recorded during the 1990 Catania Earthquake. Table 2 gives the same information for the tests in which the surcharge was applied.

Figure 3 and Figure 4, show the displacements time-history for tests Test 4 and Test 4bis respectively, in which the input motion is fixed to a frequency of 5 Hz with maximum amplitude equal to 5 mm, capable to apply a maximum acceleration of 0.5 g.

It is apparent that permanent displacements build up in the outward direction when the table is moving backwards.

The accumulation of permanent displacements was more gradual, but large oscillation appeared especially at the top of the wall from the beginning of the shaking test and increased when the wall and the table accelerations were negative, that is, directed backward. Large oscillations produced appreciable deformations of lateral facing during the test without surcharge

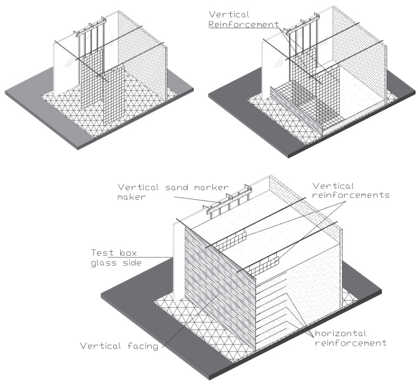

Figure 1. Sequence of the construction phases of the model.

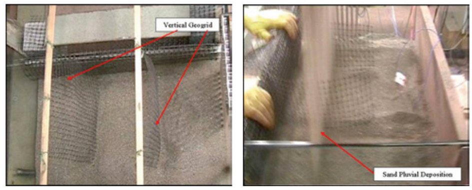

Figure 2. Particular sequence of the model construction.

Table 1. Experimental program without surcharge.

Test	Freq/Amp (Hz/mm)	Top (cm)	Base (cm)	T > B %	B>T %
1	4/4	0.28	0.16	75	–
2	4/5	0.17	0.10	70	–
3	5/4	0.17	0.05	240	–
4	5/5	0.37	0.13	185	–
5	6/2	0.02	0.01	100	–
6	6/3	0.18	0.16	13	–
7	7/2	0.41	0.29	41	–
8	7/3	0.72	0.75	–	4
7-6 failure	7/6	5.33	4.68	14	–
CT_E_W	CT_EW90	0.81	0.62	31	–

Table 2. Experimental program with surcharge.

Test	Freq/Amp (Hz/mm)	Top (cm)	Base (cm)	T > P %	P > T %
1 bis	4/4	0.27	0.12	125	–
2 bis	4/5	0.26	0.16	63	–
3 bis	5/4	0.34	0.27	26	–
4 bis	5/5	1.68	0.85	98	–
5 bis	6/2	0.03	0.03	0	–
6 bis	6/3	0.75	0.62	21	–
7 bis	7/2	0.68	0.66	3	–
8 bis	7/3	1.14	0.51	124	–
7-6 failure	7/6	5.38	4.53	19	–
CT_EW bis	CT_EW90	0.75	0.59	27	–

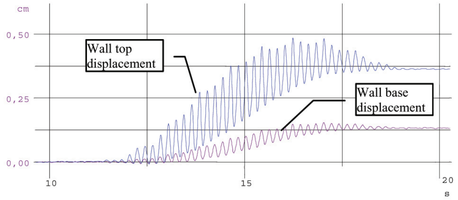

Figure 3. Displacement time-history Test 4.

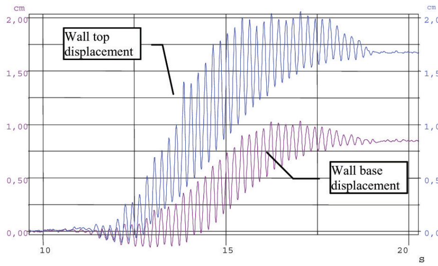

Figure 4. Displacement time-history Test 4bis.

and large deformations fduring the test with surcharge, with very large final permanent displacements recorded. Figure 5 shows the photos of the system before and after the test Test 4 bis.

Figure 6 reports Test 8 (f = 7 Hz A = 3 mm $(a/g)_{max}$ = 0.6 g) and Figure 7 the displacements time-histories recoded for the test CT_EW bis can be seen. These tests were chosen because are the most representative when compared to similar tests with a common distribution (only horizontal) of the reinforcements. These latter two tests presents similar behaviour to that of the previous test reported, with a large oscillation of the wall and a final permanent displacement gradually reached. In test 8 (Figure 6) the final permanent displacement is the same both at the top and at the base, equal to about 0.75 cm, with a typical translation failure mode. Figures 8a and 8b shows both the accelerations and displacements time-history for the Test 4. Figure 8a shows the amplification phenomena that occur at the top of the wall, with respect to the backfill acceleration, due to the large oscillation (Lo Grasso et al. 2004). In Figure 8b the amplification at the base is not evident and the acceleration of the reinforced wall is approximately equal to the input.

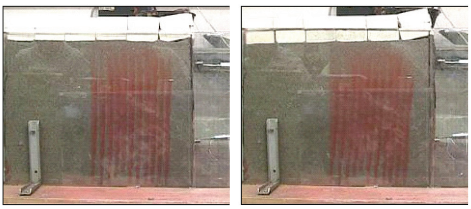

Figure 5. Test 4bis before and after the test.

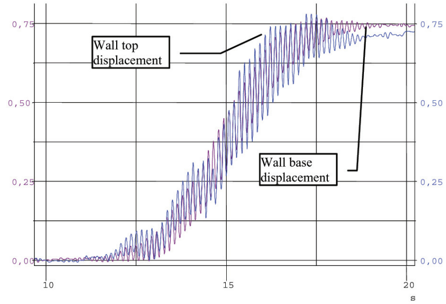

Figure 6. Displacement time-history Test 8.

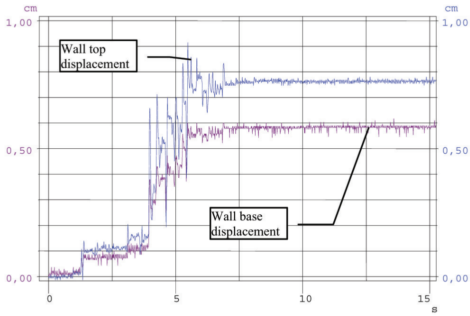

Figure 7. Displacement time-history CT EW bis.

This behaviour was more evident when the uniform surcharge was applied as shown in Figure 9. The amplification phenomena are very large and the value of the wall top acceleration shows an increment of about 50%, with a final permanent displacement of 1.65 cm. Acceleration at the base and input time-history have been omitted because it is not enough significant.

When the input frequency was increased, large oscillations effects were observed but no other evident amplification phenomena occur. Only a few peak of wall top acceleration are greater than the corresponding input value and this increment coincide with the sudden increase in permanent displacement. Similar observations can be made regarding test 8 as show in Figure 10, where are once again both the accelerations and displacements time-history at the top of the wall are reported. The accelerometric data shows that prior to threshold acceleration the wall acceleration is similar to the acceleration in the backfill; when input acceleration overcome such threshold, a cut-off acceleration for the wall is clearly evident, indicating that a relative acceleration has developed in the system and a series of amplification phenomena appear. These observation are a confirmation of the previous tests conducted with the same model but with different series of tests. (Lo Grasso et al. 2004 a, 2004 b, 2005).

Permanent displacements build up in the outward direction when the table is moving backward. This

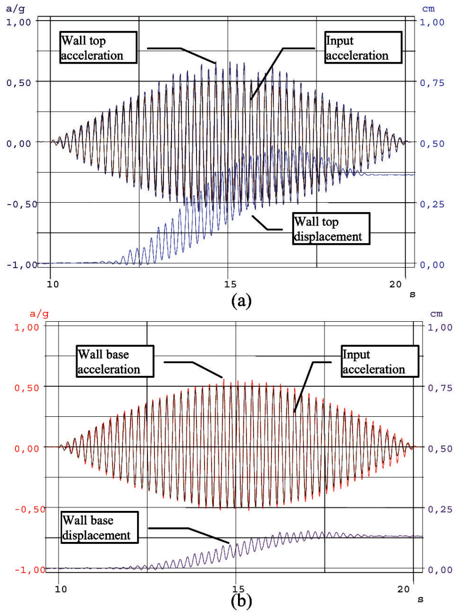

Figure 8. Test 4: (a) top and input accelerations and top displacement time-histories; (b) base and input accelerations and base displacement time-histories.

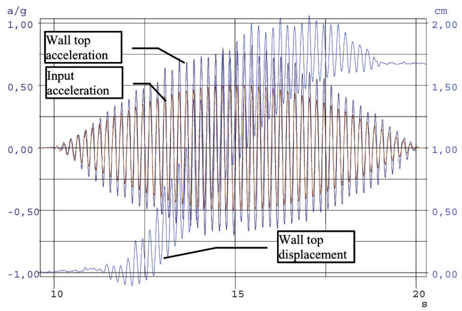

Figure 9. Test 4bis: top and input accelerations and top displacement time-histories.

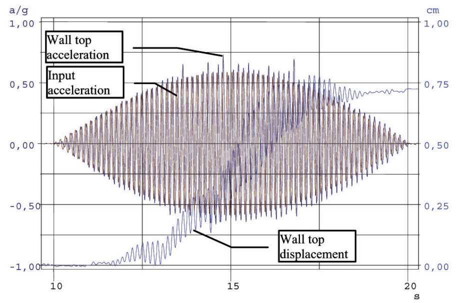

Figure 10. Test 8: top and input accelerations and top displacement time-histories.

behaviour is more evident for the accelerations in the backward direction, that is when the wall move outward.

Moreover, a difference of phase between the accelerometric records of input and the wall top is associated to the amplification phenomena recorded. This phase change in horizontal acceleration plays an important role on the distribution of the dynamic increment of the earth pressure and on the stability of the wall. (Lo Grasso et al., 2004 a, 2004 b).

4 ANALISYS AND DISCUSSION OF TESTS CONDUCTED

Observing the tests results it is possible to underline that the introduction of vertical reinforcements within the backfill produce a good response to the dynamic load, because the effects of the inertial forces are reduced and the global model stiffness is incremented. In fact, the vertical reinforcements are able to oppose greater resistance to the dynamic load that produce pull-out effect into the model along the vertical direction.

Even if the recoded data underline a very large increment in acceleration level, especially near the top of the wall, no large permanent displacement occurs, and this effect is more evident when the frequency of dynamic load predominates with respect to the amplitude. A recoverable and an irrecoverable displacement occurs for every cycle of input load (Lo Grasso et al. 2004 a, 2004 b).

Table 3 shows the values of the accelerations at the top of the wall, for all the test conducted without surcharge and Figure 11 presents a graphics of the accelerations of Table 3. In this Figure 11 the tendency to increase of the acceleration near the top of the wall can be clearly observed.

The recorded data and the deformation of vertical lateral facing shows that the frequency of the input motion influences these tests. Similar results were reported for the tests with 1 kPa surcharge in Figure 12, where the wall top maximum accelerations are reported and compared with input value. Together with the recorded data for each test, the failure surface was observed through the glass side of the test box. These observations permitted the model deformations during the motion to be analysed and give a lot of information about the reinforcement effects on the global stiffness of the model. In fact, a typical observation which occurred in all the tests is a reduction in the permanent final deformations especially if compared with similar tests carried out using only horizontal reinforcements.

The failure surfaces clearly formed at the end of each test show that only if a very high acceleration level is applied does the model record a large permanent deformation and, consequently, it is able to generate an evident failure surface. In the tests carried out, typical linear and bi-linear failure surface were observed and, in some case, also two typical linear surface.

Table 3. Recorded acceleration data for tests without surcharge.

Test	Fr/Am (Hz/mm)	Input + (a/g)	Top + (a/g)	I > T %	T > I %	Test	Fr/Am (Hz/mm)	Input– (a/g)	Top– (a/g)	1 > T %	1 > T %
1	4/4	0.25	0.39	–	56.0	1	4/4	–0.25	–0.28	–	12.0
2	4/5	0.32	0.48	–	50.0	2	4/5	–0.32	–0.33	–	3.1
3	5/4	0.40	0.43	–	7.5	3	5/4	–0.40	–0.41	–	2.5
4	5/5	0.50	0.65	–	30.0	4	5/5	–0.50	–0.62	–	24.0
5	6/2	0.29	0.32	–	10.3	5	6/2	–0.29	–0.36	–	24.1
6	6/3	0.43	0.50	–	16.3	6	6/3	–0.43	–0.52	–	20.9
7	7/2	0.39	0.48	–	23.1	7	7/2	–0.39	–0.51	–	30.8
8	7/3	0.59	0.71	–	20.3	8	7/3	–0.59	–0.67	–	13.6
7–6 failure mode	7/6	1.18	1.58	–	33.9	7–6 failure mode	7/6	–1.18	–1.50	–	27.1
CT_EW	CT_EW90	0.80	1.00		25.0	CT_EW	CT_EW90	–0.80	–0.70	14.3	–

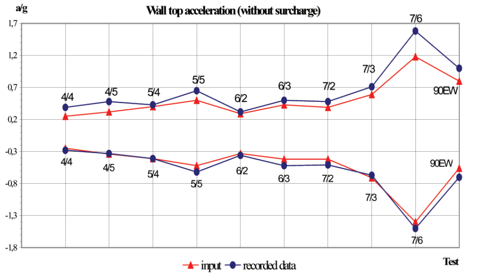

Figure 11. Acceleration amplification values at the top of the wall for the test without surcharge.

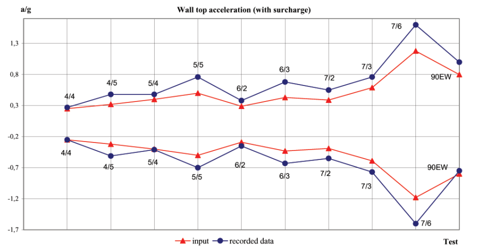

Figure 12. Acceleration amplification values at the top of the wall for the test with surcharge.

Table 4 carries a a summary which indicated the failure surface formed and the relative angle with respect to the horizontal foe each test.

Figure 13 shows some photos of two tests without surcharge and two tests with surcharge, at the end of the dynamic input, where the failure surfaces are formed can be observed and where are indicate the relative angle in respect to the horizontal.

Comparing the tests reported in this paper with those conducted in previous tests program, in which the reinforcement distribution is only in the horizontal direction, is possible to underline clearly the beneficial effects deriving from the three-dimensional placement.

To permit a direct comparison between the reinforced model systems, some photos of similar tests (with the same input characteristics and boundary condition) are presented.

Table 4. Failure surface formed and relative angle with respect to the horizontal

Test	Fr/Am (Hz/mm)	SERIE 1 Failure surface	SERIE 1 Inclination (°)	SERIE 1 bis Failure surface	SERIE 1 bis inclination (°)
1	4/4	–	–	–	–
2	4/5	–	–	–	–
3	5/4	–	–	–	–
4	5/5	–	–	linear	21
5	6/2	–	–	–	–
6	6/3	–	–	Bi-linear	31–42
7	7/2	–	–	linear	38
8	7/3	Bi-linear	32-39	Bi-linear	32-47
7-6 failure mode	7/6	linear	24	2 linear	28-34
CT_EW	CT_EW90	linear	32	linear	30

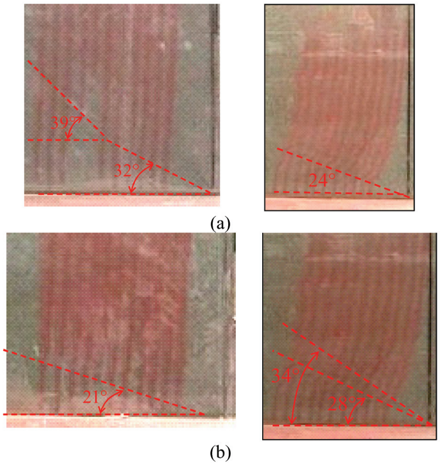

Figure 13. Tests without surcharge (a) and tests with surcharge (b) at the end of the dynamic input.

Figure 14 a represents the photos for Test 3 (f = 5 Hz, A = 4 mm), Figure 14b those for Test 8 (f = 7 Hz,

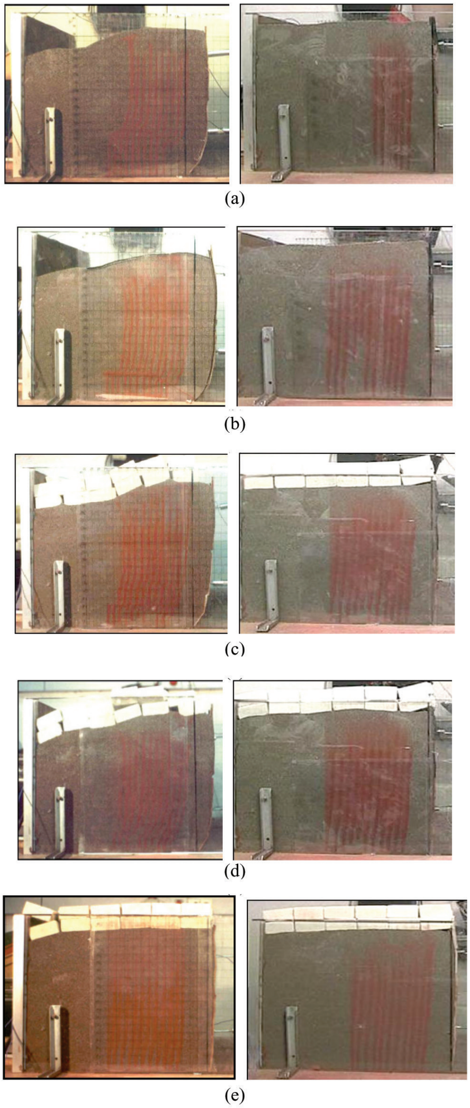

Figure 14. On the left the systems with 2D reinforcements and on the right the systems with the 3D reinforcements: (a) Test 3 (f = 5 Hz, A = 4 mm), (b) Test 6 (f = 6 Hz, A = 3 mm), (c) Test 8 (f = 7 Hz, A = 3 mm), (d) Test 4bis (f = 5 Hz, A = 5 mm), (e) Test 8bis (f = 7 Hz, A = 3 mm) (f) Test CT_EW

A = 3 mm), Figure 14c those for Test 4bis (f = 5 Hz, A = 5 mm), Figure 14d those for the Test 8bis (f = 7 Hz, A = 3 mm) and, finally, Figure 14e the photos for the test CT_EW.

5 CONCLUSIONS

In this paper, the tests carried out show that: the distribution of reinforcement under seismic condition play an important role in global stability; the three-dimensional distribution of reinforcement produces a good response during motion and allows little permanent deformation compared to a bi-dimensional distribution. The failure mechanism and the surcharge effects were also investigated.

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