DYNAMIC MODEL TESTS ON L-SHAPED GRAVITY RETAINING WALLS

Ernesto CASCONE[1], Simone LO GRASSO[2] And Michele MAUGERI[3]

SUMMARY

Seismic design of retaining walls is traditionally based on the Mononobe-Okabe method of analysis. This method is an extension of the classical wedge theory in which both vertical and horizontal inertia forces are introduced in order to take into account the effect of earthquake shaking on the thrust acting on the wall.

In recent years a number of theoretical analyses have been presented to predict the seismic behaviour of gravity retaining walls. Although all these studies provided interesting results, there is the need of experimental evidence and documented real cases. In this paper some shaking table tests performed on a L-shaped gravity wall retaining dry sand are described and the experimental results are presented with the aim to provide, though qualitatively, an insight into some important aspects of the dynamic behaviour of retaining structures resting on rigid foundation soil. Two different systems have been taken into consideration, namely, a wall retaining a horizontal backfill and a wall retaining an inclined backfill. During tests, both accelerations and wall displacements were measured. Through the transparent sides of the test box it was possible to observe the development of the failure surface and to measure the angle formed by such surface to the horizontal axis.

INTRODUCTION

Seismic design of earth retaining walls is conventionally carried out by means of the Mononobe-Okabe theory, which is an extension of the classical solution due to Coulomb and Rankine for the evaluation of the earth pressure in static conditions. According to the pseudostatic Mononobe-Okabe theory, the effect of earthquake shaking on the lateral earth pressures acting against the wall can be modelled by simply introducing in the limit equilibrium equation of the soil failure wedge, the inertia forces developing in the soil because of a seismic acceleration assumed constant. Although it is generally agreed that walls resting above the water table and retaining dry soil, if properly designed according to Mononobe-Okabe theory, did not experience severe damage in past earthquake [Whitman 1991], in recent years seismic failures and damages of earth retaining walls have been documented. In fact, Tateyama et al. [1995], for example, reported on damages and failures of traditional gravity and cantilever retaining walls occurred during the 1995 Kobe earthquake.

In order to take into account the accumulation of permanent displacement in the seismic design of retaining walls extensive studies have been carried out in the last 20 years. Those studies were mainly devoted to the prediction of permanent displacements by either the formulation of empirical relationships based on numerical analysis [Richards and Elms 1979, Zarrabi 1979, Whitman and Liao 1984, Crespellani et al 1996] or the modelling of

[1] *Faculty of Engineering, University of Catania, Italy. Tel ++39-095-7382205*
[2] *Faculty of Engineering, University of Catania, Italy. Tel ++39-095-7382205*
[3] *Faculty of Engineering, University of Catania, Italy e-mail: mmaugeri@isfa.ing.unict.it*

dynamic soil-structure interaction [Nadim and Whitman 1983, Siddharthan and Norris 1991, Cascone et al. 1994, Prakash et al. 1995, Caltabiano et al. 1999a].
Experimental studies have been performed as well, using either shaking table or centrifuge facilities. Efforts were addressed to the experimental evaluation of lateral soil pressure distribution [Sherif et al. 1982, Ishibashi and Fang 1987] and to the observation of wall displacements [Bolton and Steedman 1984, Al-Homoud and Whitman 1995, Cascone and Maugeri 1995, Oldecop et al. 1996]. In this paper the result of some shaking table tests are reported. The tests were carried out on two different systems: a wall retaining a horizontal soil backfill and a wall retaining a sloping soil backfill. The wall chosen for the tests presents an L-shaped cross section and resists against driving static and dynamic forces by means of its own weight and of the weight of the soil resting on the foundation slab.

TESTING PROCEDURE

The shaking table available at the laboratory of the University of Catania was described by Cascone and Maugeri [1995] and is shown in Fig.1. The table consists of a steel frame and a steel plate bolted on the frame, it is 2 m long, 1m wide and 80 mm thick and is supported by four rollers constrained to move on rails, in order to restrict the motion only to one direction. The motion is provided to the table by a loading unit consisting of an electric trhee-phase synchronous engine with a steel disk mounted on the engine shaft. The position of the disk is adjustable allowing to produce different eccentricities in the range 1-10 mm.
The motion is transferred from the engine to the table by means of a ball-bearing placed on the edge of the table. The contact between the disk and the bearing is maintained by a spring fixed on a contrast beam and kept compressed throughout the dynamic testing. A test box 0.9 m long, 0.7 m wide and 0.4 m deep is fixed to the table. The sides of the box are made of transparent glass and allow the observation of the model during the test. The thickness of the glass sides was chosen equals to 10 mm in order to reproduce a plane-strain condition.
Studies related to static tests on model of retaining structures report somewhat contrasting opinions [Arthur and Ruscoe 1965, Rowe 1970, Bransby and Smith 1975] about the lateral friction between the soil and the sides which may affect the formation of the failure surface in the backfill. In order to minimize this effect, the glass sides were treated with a chemical solution.
In order to provide adequate friction between the soil and the test box a sheet of cardboard, previously roughened by glueing sand on it, was fixed on the base of the box. The wall used in the tests is a microconcrete retaining wall of height H=cm 25 consisting of a vertical stem 3 cm thick and a horizontal slab 10.5 cm wide and 2.5 cm thick. In order to avoid friction between the wall and the glass sides of the box, the wall was made 5mm shorter than the box width and the wall ends were equipped with flexible plastic flags to prevent sand passing through the lateral gaps. The sand used in the test is uniform (D_{60}/D_{10} = 1.60) with small (D_{50} = 0.3 mm) sub-angular grains, maximum and minimum unit weight γ_{max} = 16.8 KN/m^3 and γ_{min} = 14.5 KN/m^3, respectively, and peak value of the angle of shear strenght φ = 35°. Dry silica sand was pluviated in the test box from a constant height of 70 cm, at a relative density D_R = 85%. The effect of relative density on the angle of shear strenght for this sand, was shown to be negligible [Lo Grasso 1999]. In each 7test the wall was instrumented with two

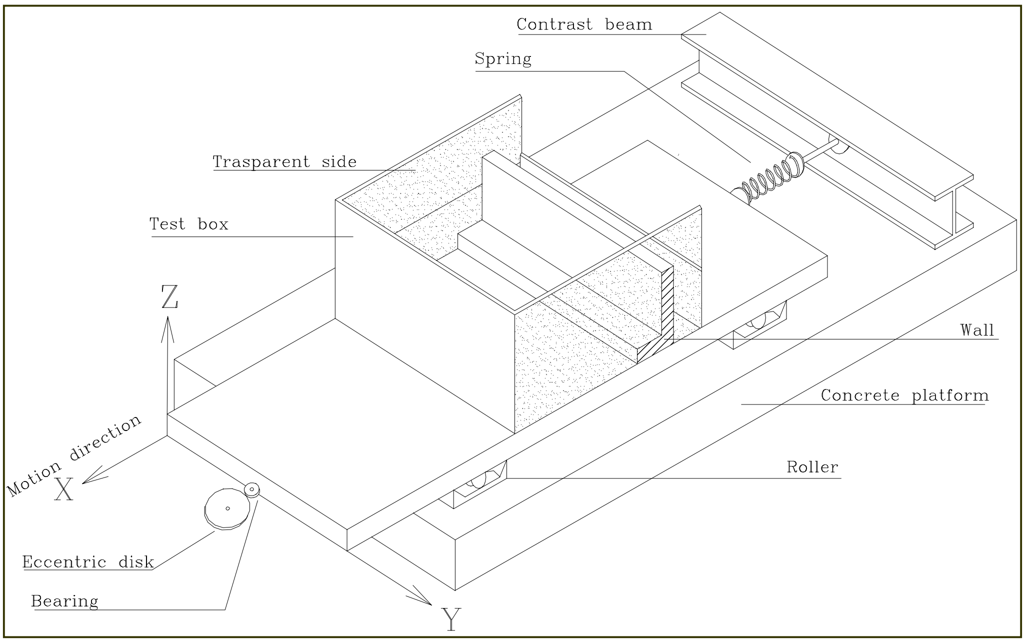


Figure 1: Experimental set-up

accelerometers and two LVDT displacement transducers to record both accelerations and displacements at the top and at the base; two accelerometers were placed in the backfill: one at a depth of 22 cm and the other almost at the backfill surface; one additional accelerometer was fixed on the table to record the input motion. A data acquisition system and a software for data processing were employed to record and analyze data obtained during dynamic testing. In order to detect the formation of the failure surface in the backfill, vertical black sand markers were introduced in the model.

TEST RESULTS AND DISCUSSION

The soil-wall system were subjected to an input acceleration slowly increasing with time. In fact, the table displacement was adjusted at 4 mm and both table frequency and acceleration were varied until a failure surface was clearly distinguished through the glass sides of the test box.

Figure 2 shows a sketch of the wall retaining a horizontal soil backfill after the development of a clear failure surface. It is easy to observe that the soil resting on the wall foundation slab moved together with the wall and that the failure surface originates at the heel of the wall and can be approximated to a plane, inclined of 47° with respect to the horizontal. The time-histories of accelerations and displacements of this soil-wall system are shown in Fig.3. In particular, Fig. 3a shows the input acceleration and wall top and base displacements for the last 30 seconds of the test. In the initial 100 seconds the accumulation of permanent displacement was negligible, while the input motion frequency was varying from 2.9 to 6.8 Hz and the table maximum acceleration was consequently increasing from 0.08g to 0.36g.

Displacements started to build up in the interval from 104 sec to 119 sec, at a frequency of about 7 Hz and table maximum acceleration 0.44÷0.47g. Finally, a further increase of the frequency up to 7,3 Hz brought the table maximum acceleration up to 0.49g, producing a sudden accumulation of permanent displacements. Displacements reached 0.95 cm at the base of the wall and 1.20 cm at the top of the wall, showing a slight permanent rotation. Only at this stage the formation of the failure surface was observed through the glass sides of the test box and the shaking table was stopped. In Fig.3b the table acceleration and the wall top acceleration and displacement time-histories are plotted for a short interval. It is possible to observe that top displacements have large oscillations and increase when the wall and the table acceleration are negative, that is, directed backward.

Likewise, in Fig.3c the table acceleration and the wall base acceleration and displacement time-histories are plotted for the same short interval. It is apparent that permanent displacements build up in the outward direction when the table is moving backward. The displacement build-up follows a stepwise pattern alternating phases of relative motion, in which the wall moves relatively to the table, and phases of absolute motion, in which the wall moves together with the table. In agreement with other experimental results [Richard and Elms 1990], in any cycle of motion the wall acceleration becomes less than the input acceleration and is almost constant, producing a sort of “plateau”. Fig.3d shows the comparison between the acceleration of the table and the acceleration recorded at the surface of the backfill. A slight amplification can be observed for negative accelerations showing the tendency of the system to rotate in the last seconds of excitation. Finally, Fig.3e shows the comparison

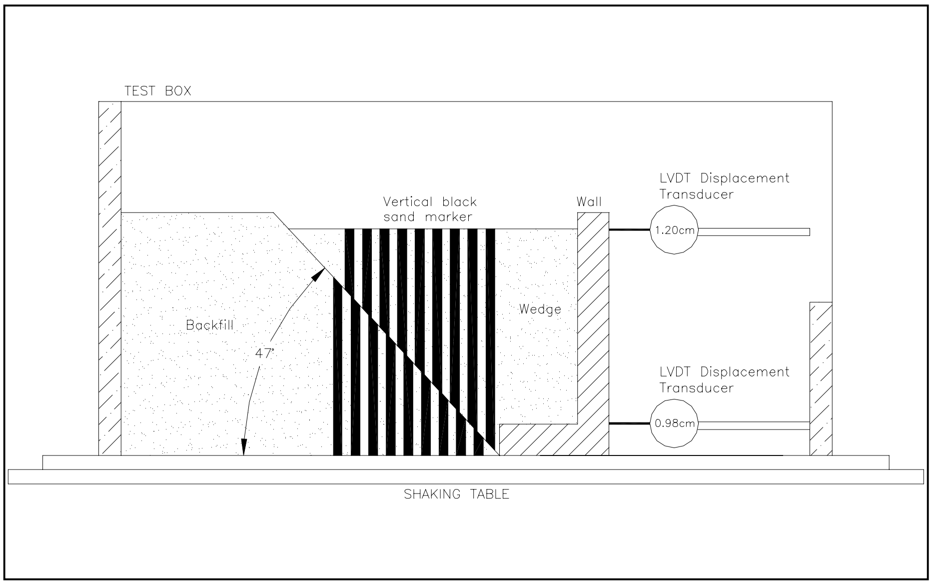


Figure 2: sketch of the wall retaining a horizontal soil backfill after the development of a clear failure surface

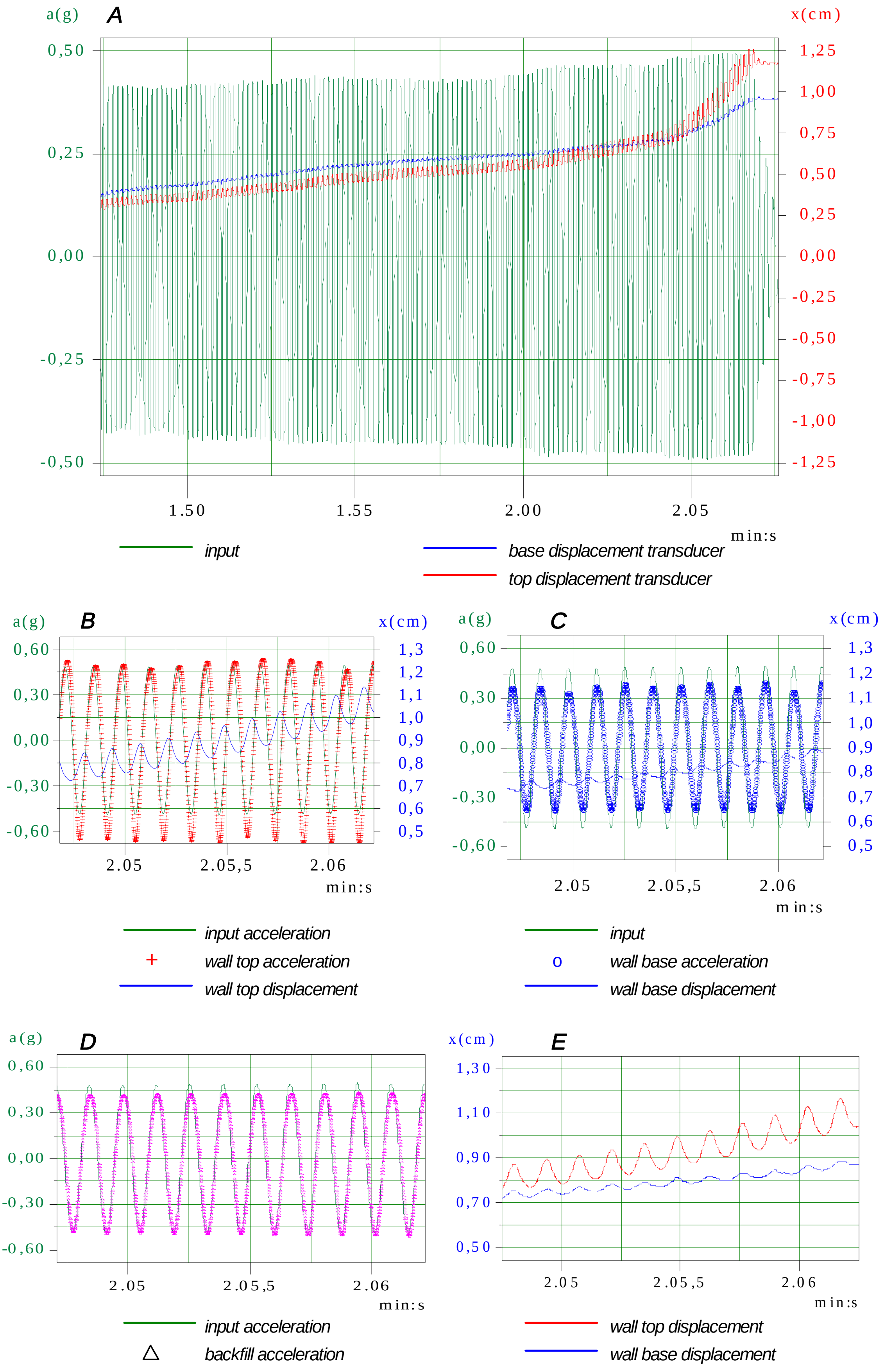


Figure 3: Wall with horizontal soil backfill: time-histories of accelerations and displacements.

between the wall top and base displacements. Top displacements present large amplitude oscillations due to the top of the wall moving back and forth during shaking. Base displacements present oscillation as well, due to the fact that the accelerometer is placed at a certain height (3 cm) from the base of the wall. The final permanent rotation is quite small and is due to the sand introducing underneath the wall heel during wall rocking.
Figure 4 shows photographs of the wall retaining a sloping soil backfill before the test (Fig 4a) and after the formation of the failure surface in the backfill (Fig.4b) The angle of the sloping backfill is $\beta = 15°$. Also in this case, as expected, the soil resting on the wall foundation slab moved together with the wall, while the failure surface inclined of about 46° shows a small concavity. Finally Fig.4c shows the system after further displacements which brought the soil-wall system to a condition of collapse. It is possible to see different failure surfaces. In general, for translational displacement, the failure surfaces developing after the first one are internal to the first failure wedge [Caltabiano et al. 1999a]. In this case it is possible to explain the second failure surface, external to the previous wedge, as a consequence of a slope failure mechanism due to the fact that the wall, after having suffered large displacements, is not capable to retain the backfill.
Time-histories of recorded accelerations and displacements are plotted in fig.5. Most of the features observed in the test of the wall retaining a horizontal backfill can be recognized, even with more evidence in the results of this test: wall top negative accelerations larger (in value) than input accelerations at failure indicating some rotation of the top of the wall (Fig.5b); wall base positive accelerations smaller than input accelerations at failure showing a typical plateau (Fig.5c); no appreciable amplification is observed in the backfill (Fig.5d); almost no appreciable permanent rotation is accumulated, in fact the final wall top and base displacements are 1.82 cm and 1.76 cm respectively. Also this test was stopped when the failure surface was detected through the glass sides of the test box.
Comparing the results of the two tests it is possible to conclude that both the systems considered in the experimental programme exhibit a basically translational failure mode. This mechanism can be partly attributed to the rigid foundation condition and to the absence of any embedment in front of the wall. In fact some rotation might have been expected if the wall was resting on a compliant soil and/or presented even a small embedment creating a restrain to sliding. For the case of wall with horizontal backfill, displacements started when the maximum table acceleration became as high as 0.25g, while the failure surface appeared for a maximum table acceleration equal to 0.49g.
For the case of wall with sloping backfill, displacements started when the maximum table acceleration reached 0.1g and the failure surface appeared for a maximum table acceleration as high as 0.32g. These marked differences are obviously due to the different boundary condition: the sloping backfill exerts a larger thrust and involves larger inertia forces with smaller accelerations. Critical accelerations and failure surface angle computed for the two systems using the relationships proposed by Caltabiano et al. [1999a and b] resulted:

- Wall with horizonthal backfill $a_{cr} = 0.21g$ $\alpha = 48.6°$
- Wall with sloping backfill $a_{cr} = 0.11g$ $\alpha = 46.0°$

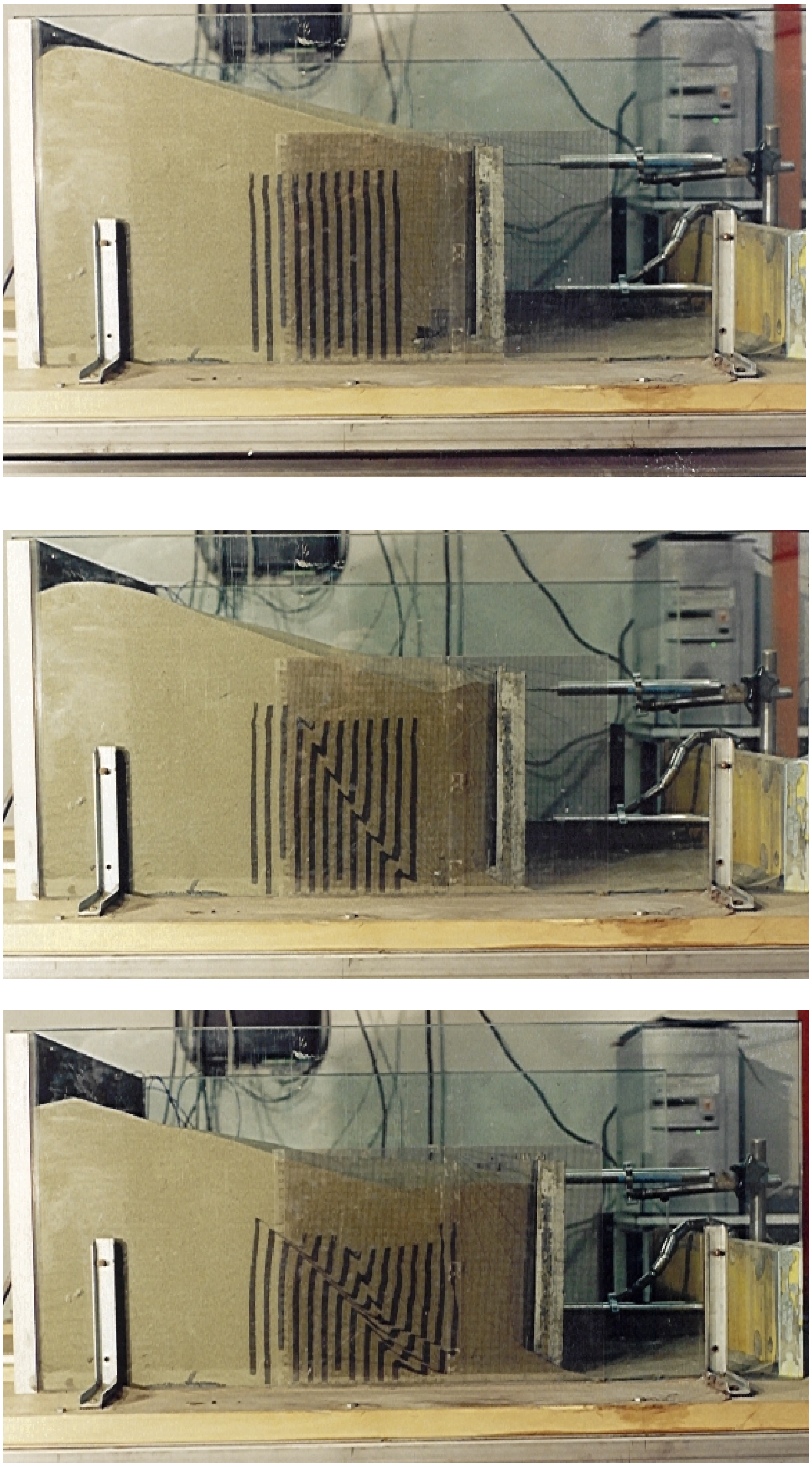
CONCLUDING REMARKS

Shaking table test on two different soil-wall system were carried out and the following conclusions were drawn:

- The behaviour of L-shaped walls resting on rigid foundation under dynamic loading is basically translational;
- The soil mass partecipating to the system motion is the mass resting on the wall foundation slab and the mass of the failure wedge;
- Acceleration required to produce wall displacements are higher for the case of horizontal backfill and compare well with those computed according to the theoretical models by Caltabiano et al. [1999a and b];
- The failure surface angles measured experimentally compare well with those computed according to the theoretical models by Caltabiano et al. [1999a and b];
- The system with sloping backfill at large displacement, exhibits a slope failure mechanism.

REFERENCES

[1] Al-Homoud A.S., Whitman R.V., 1994 Comparison Between the Prediction and Results from Dynamic Centrifuge Test on Tilting Gravity Walls". *Soil Dynamics and Earthquake Engineering, Vol 14, 1994.*
[2] Bolton M.D., Steedman R.S., 1984. "Modelling the Seismic Resistance of Retaining Structures", Proc 1th *International Conference on SMFE, San Francisco, CA, USA, 1984*.
[3] Al-Homoud A.S., Whitman R.V., 1994 Comparison Between the Prediction and Results from Dynamic Centrifuge Test on Tilting Gravity Walls". *Soil Dynamics and Earthquake Engineering, Vol 14, 1994.*
[4] Bolton M.D., Steedman R.S., 1984. "Modelling the Seismic Resistance of Retaining Structures", Proc 1th *International Conference on SMFE, San Francisco, CA, USA, 1984*.



A

B

C

Figure 4: Wall with sloping backfill: A) at rest; B) after the formation of the failure surface; C) at collapse.

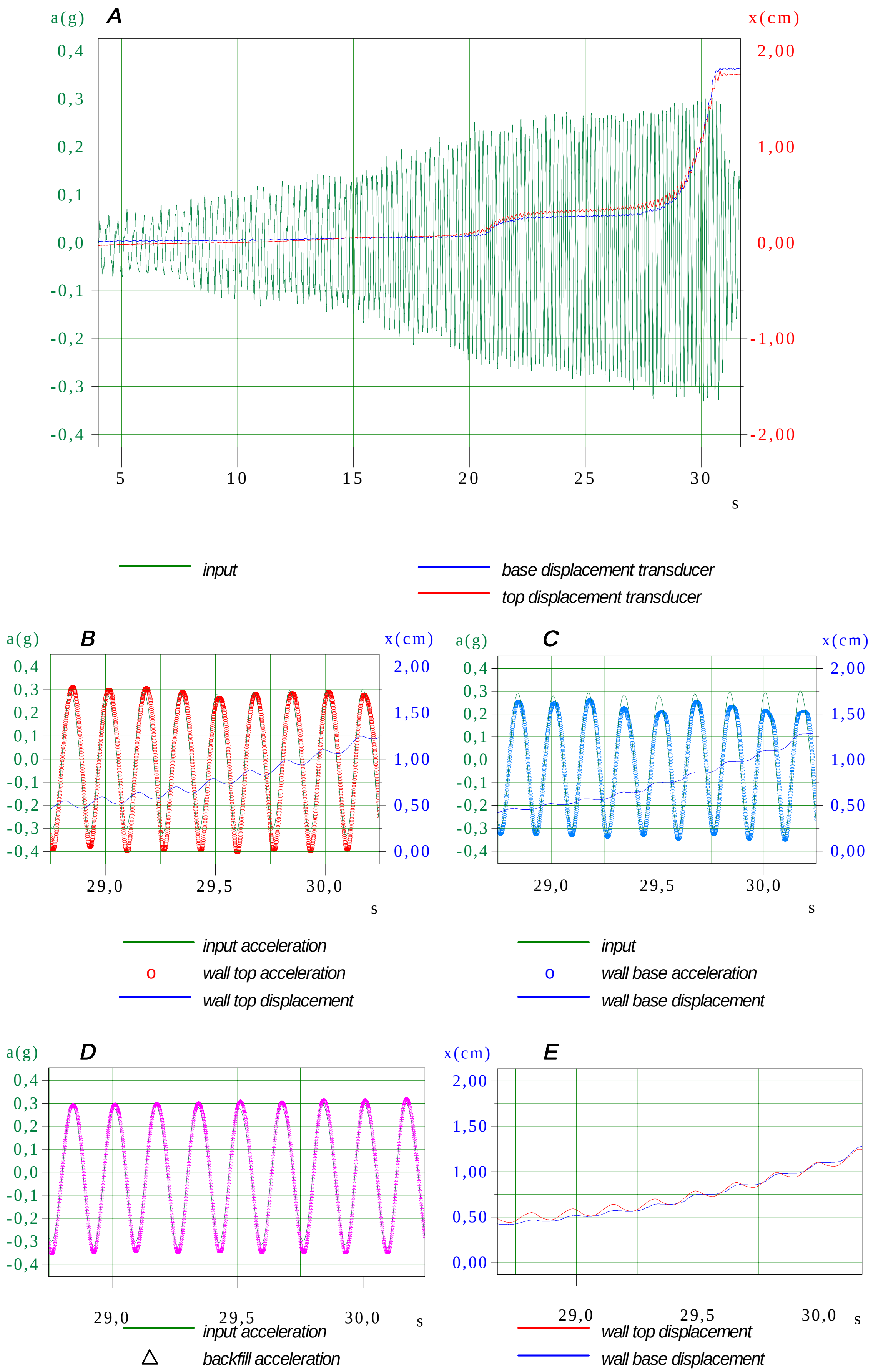


Figure 5: Wall with sloping backfill: time-histories of accelerations and displacements.

[5] Caltabiano S., Cascone E., Maugeri M., 1999a. "Sliding Response of Rigid Retaining Wall". *Proc. International Conference on Earthquake Engineering, Lisbon, 1999*.

[6] Caltabiano S., Cascone E., Maugeri M., 1999b. "Seismic Stability of Retaining Walls with Surcharge". *Proc. IX International Conference on Soil Dynamics and Earthquake Engineering, Bergen, August 1999*.

[7] Cascone E., Maugeri M., Motta E., 1994."Risposta Sismica dei Muri di Sostegno a Gravità". *Rivista Italiana di Geotecnica, Vol. XXVII, N.4, 1994.*

[8] Cascone E., Maugeri M., 1995. "Shaking Table Test of Gravity Retaining Walls". *Proc. 7th International Conference on Soil Dynamics and Earthquake Engineering, Chania, Greece, 1995*.

[9] Crespellani T., Madiai C., Vannucchi G., "Earthquake destructiveness potential factor and permanent displacement of gravity retaining walls". *Session on Analysis and Design of Retaining Structures Against Earthquake, ASCE Annual Convention, Washington DC.*

[10] Ishibashi I., Fang Y.S.. "Dynamic Earth Pressures with Different Wall Movement Modes". *Soils and Foundation, Vol.27, N.4, 1987.*

[11] Lo Grasso A. S., 1999. "Effect of a surcharge on the dynamic behaviour of retaining walls by shaking table test". *Diploma Thesis*, University of Catania, Italy, in Italian, unpublished: pp.350.

[12] Nadim F., Whitman R.V.,1983 "Seismically Induced Movement of Retaining Walls". *Journal of the Geotechnical Engineering Division, ASCE, Vol.109, N.7, July 1983*.

[13] Oldecop L., Zabala F., Almazan J.L., 1996 "Shaking Table Test on Small Prototype of Soil Retaining Wall", *Proc., 11th World Conference on Earthquake Engineering, paper N. 1094, 1996*.

[14] Richards R., Elms D.G., 1979 "Seismic behaviour of gravity retaining walls", *Journal of Geotechnical Engineering Division, ASCE, 1979, Vol.105(4), 449-465*.

[15] Richards R., Elms D.G., 1990. "Seismic Design of Retaining Wall". *Proceedings of the Conference on Design and Performance of Earth Retaining Structures, Ithaca, USA, ASCE Geo-Special Publ. 25, 1990, 854-871*.

[16] Sherif M.A., Ishibashi I., Lee C.D., 1982. "Earth Pressure against Rigid Retaining Walls". Journal of Geotechnical Engineering, ASCE, Vol.108, 1982.

[17] Siddharthan R., Norris G.M., 1991. "On the Seismic Displacement Response of Rigid Retaining Walls". *Soil and Foundation, Vol31, N.2, 1991*.

[18] Tateyama M., Tatsuoka F., Koseki J., Horii K., 1995. "Damage to Soil Retaining Walls for Railway Embankments during the Great Hanshin-Awaji Earthquake". *Proc., Ist International Conference on Earthquake Geotechnical Engineering, Tokio, Japan, 1995*.

[19] Whitman R.V., 1991. "Seismic Design of Earth Retaining Structures". *Proc., 2nd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri, 1991*.

[20] Whitman R.V., Liao S., 1984. "Seismic Design of Gravity Retaining Walls". *Proc., 8th World Conference on Earthquake Engineering, San Francosco, Vol3, 1984*.

Zarrabi-Kashani K., 1979. "Sliding of Gravity Retaining Walls during Earthquake Vertical Acceleration and Changing Inclination of Failure Surface". *M.S. Thesis, Dept. Of Civil Engineering MIT, Cambridge, USA, 1979.*