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EARTHQUAKE RISK REDUCTION OF LANDSLIDES

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SUMMARY

The paper deals with an innovative technique for reducing the risk of landslides in seismic prone areas with the aid of reinforced-soil structures. The innovation consists in using a system of self-confined retaining structures. Three generations of models for reinforced-soil retaining-walls were successively tested on the shaking tables of two EQ Engineering Laboratories, INCERC Iasi, Romania and Bristol University, UK. The research programs had the practical scope to determine the settlements and horizontal displacements at constant volume of infill, the acceleration responses with relative amplification and attenuation phenomena, as well as soil-structure interaction. Since the analysis-assumptions provided by BS 8006:1995 are no longer valid for seismic actions, the paper suggests a comparative program on two full scale models to be tested on the shaking table. The program will include soil-structure interaction and appropriate technologies for confining soil structures.

INTRODUCTION

According to Romanian "National Strategy for Sustainable Development", within the year 2010 the planning for the entire territory should be completed. This task also involves the stabilisation of sliding slopes, mainly those located in seismic zones. Nowadays, there are 45,000 ha of active slopes that are menacing agricultural land, public roads and farm-houses. Frequent earthquakes are activating the slopes. In addition, climate change could aggravate the phenomena of natural hazards. At the same time, the huge task of the intervention calls for a financial effort to be kept realistic and affordable, which becomes a real possibility with the consolidation method based on reinforced soil structures.

The first modern-day design approach for reinforced-earth structures was developed in the 1960s by French engineer Henry Vidal. First structures of reinforced soil used metallic reinforcement. In the seventies in Britain it was started the production of polymer grids by the extrusion under controlled heating of high-density polypropylene. During stretching the randomly oriented long-chain polymer molecules are drawn to an ordered and aligned state, which highly increases the tensile strength and stiffness of the grids. This synthetic reinforcement proved to be appropriate for reinforcing retaining-walls and steep slopes. The competitiveness of self-retaining structures won them quickly a world-wide

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diffusion. During the last two decades many were built even in Japan, where earthquakes are recurrent (Jones [1]).

The year 1995 was a decisive year for the development of reinforced soil-structures. And it was there that these structures passed the most severe of tests: the Hyogo-Ken Nambu Earthquake (17^{th} January 1995, ML 7.2) that hit Kobe and destroyed most of its infrastructures, but left unaffected most of soil-reinforced structures. To quote some walls: Amagasaki and Tsukamoto remained intact, whilst at Tanata occasional displacement was hardly measurable. From then on seismic behaviour of reinforced soil structures was unquestioned. In the same year it was published British Standard BS8006 "Code of practice for strengthened/reinforced soils and other fills", which together with DIN 4017 quickly established basic design provisions. Meanwhile many CAD programs have become available: design became much easier and that too has been contributing to the wide diffusion of this reinforcement technique. Construction technologies are also easily adaptable to any site. The quantity of geogrids used as reinforcement increases with the wall height, but reinforcement consumes remain under 2 daN/m^3 for vertical walls up to 10m, which make these structures very cost effective. Typical reinforced soil walls are massive structures. Indeed, the ratio between their base lengths L and heights H, the so-called aspect ratio L/H, is usually equal or higher than 0.6. That means the behaviour of these retaining structures is governed by gravity. Under any combination of loading the resultant of all forces acting on them is always eccentric to their bases. Sometimes, when lateral loads increase and are dominant, the eccentricities exceed the middle third of the base and unequal settlements could occur. An innovative solution is to confine the reinforced soil retaining walls.

The procedure of confining consists of inducing, with the aid of steel cables or membranes of high tensile-resistance, forces opposite to the active ones. A typical confining force is applied at or near the top of the reinforced soil structure. It consists of two components: one horizontal, acting as an anchoring force and another one vertical, parallel to structure-facing, acting in the gravity direction as an additional compressing force. Its magnitude is chosen such as to counter the eccentricity derived from the equilibrium equation of all forces acting on structure base. There is a unique value of the confining force for any given case of loading. It assumes around 20% of the structure-weight what is easily carried by steel cables. When loading fluctuates, non-zero eccentricities accordingly occur. Generally, they remain small comparing with the third half of base. However, if necessary more appropriate values for the confining force can be derived similarly. The idea of confining the retaining walls of reinforced soil is based on the Romanian Patent RO 112 040:1995 (Sofronie [2]). Confinement allows the reduction of the aspect ratio to a mere 0.4. Comparative tests between reduced scale models on shaking-tables have shown that these slender soil-structures, under seismic actions have a better behaviour than the much thicker ones (Taylor [3]).

FIRST GENERATION OF MODELS

The former shaking table of Bristol University had only a 3x3m platform. However, at that date a shear stack of 5m in length and 1x1m in cross section was available. It was used to set-up the first model of a retaining wall in reinforced soil. It was rather small for a prototype, but it was the first ever tested on a shaking table in Europe. The model was designed according to BS 8006:1995 relative to conventional or traditional reinforced soil retaining walls. As the idea of confining soil structures was already well defined, the same stack was used for a comparative model and potential alternative constructing solution (Sofronie [4], Uchimura [5]). Both models had wooden facings fixed with hinges at their bottoms, and the same geogrids were used as reinforcement. The difference between models was the aspect ratio, 0.6 for the conventional wall and 0.4 for the confined one (Fig. 1).

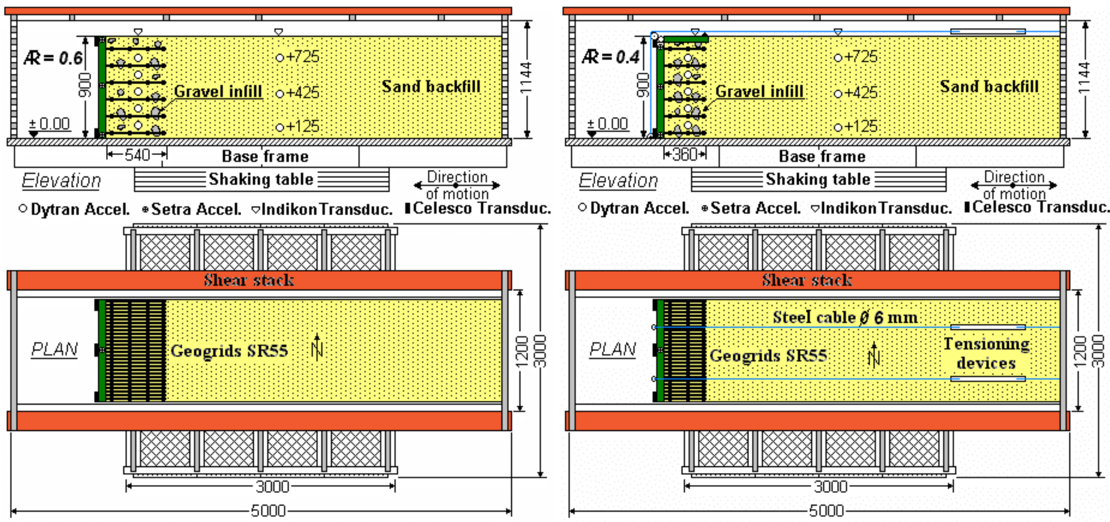

Figure 1: The pair of models tested on the shaking table of Bristol University in 1998

Both models were successively tested to the same inputs of increasing intensities, according to El Centro'40, Eurocode 8 and sine dwell of 5 Hz. The recorded data were used to draw up the diagrams of settlements, horizontal displacements and response accelerations as already reported (Sofronie [6]). Two analytical models were then used for numerical validation of the results (Fig. 2).

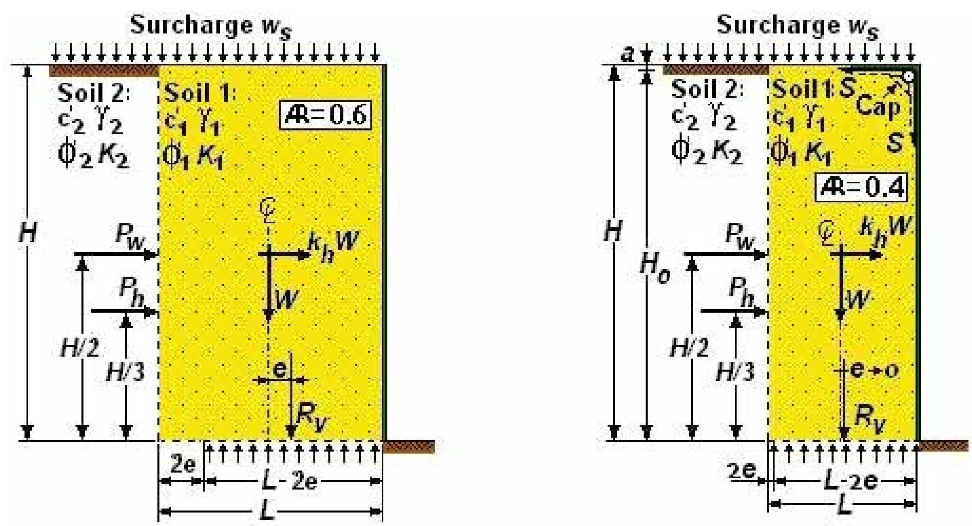

Figure 2: The computing actions of the two typical cross-sections of retaining structures

SECOND GENERATION OF MODELS

A box of steel-sheet reinforced with ribs and having the same dimensions like the above mentioned shear-stack was built. It was used for two similar models of retaining-walls with identical wooden facings but moving freely. As for the second model, a self-confining system was achieved by anchoring the two steel cables through pivots in the backfill of models. Besides the simplicity of controlling, the tensions in cables remain almost constant during seismic excitation. The two models were successively tested at the Laboratory of Earthquake Engineering of INCERC in Iasi, Romania (Fig. 3).

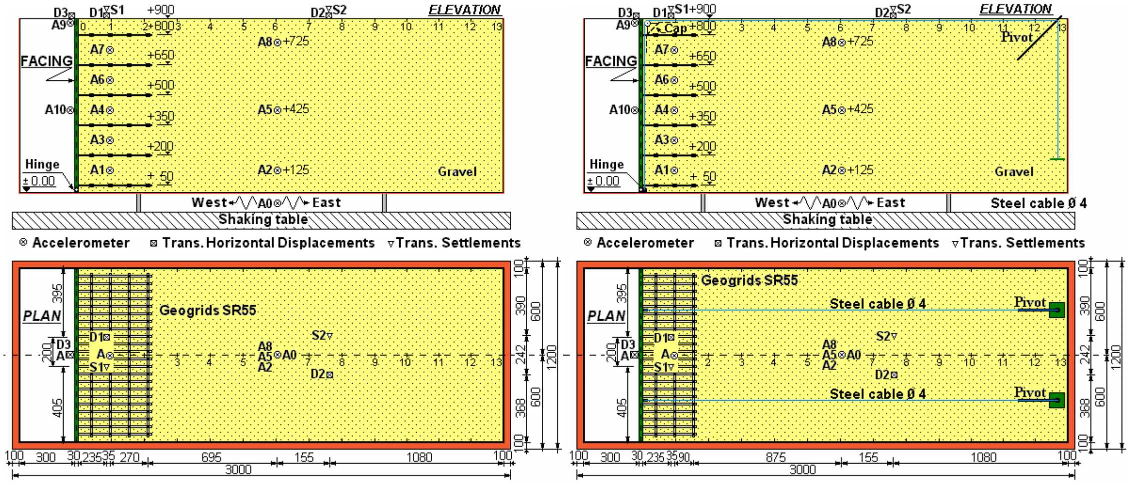

Figure 3: The pair of models on the shaking table of INCERC Iasi in 1999

Similar data have been recorded, processed and reported (Sofronie [7]). The steel box did not spoiled in any way the seismic response of the reinforced soil structures. Instead, the self-confining system proved to be efficient.

THIRD GENERATION OF MODELS

The aim of the third program was to test the soil-structure interaction with the aid of other two models on the shaking table of Bristol University (Fig.4). For that purpose an elastic structure of steel with one DOF

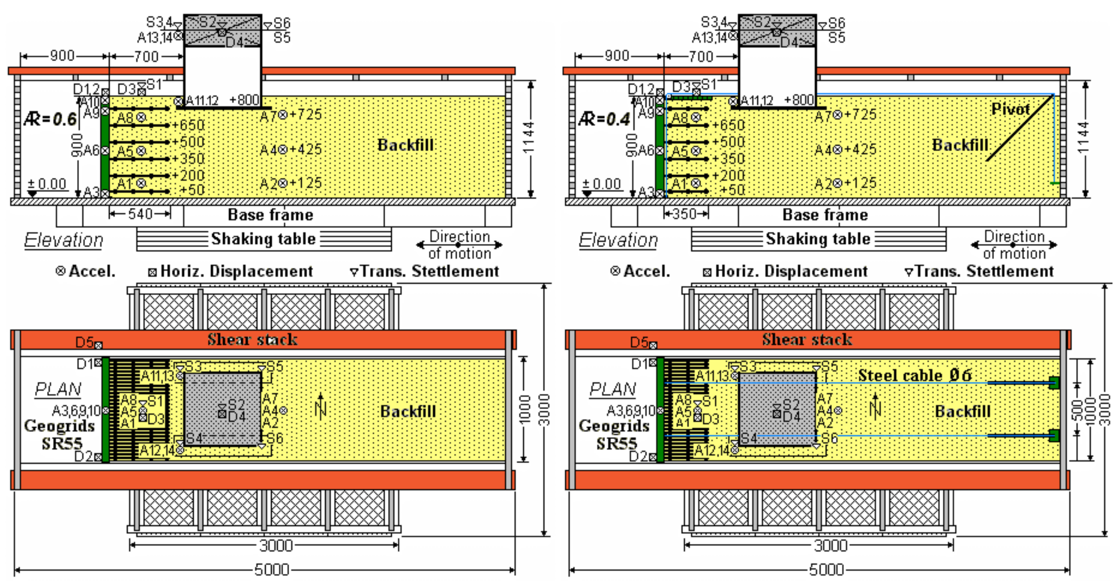

Figure 4: The pair of models tested on the shaking table of Bristol University in 2000

was specially designed. The platform of elastic structure allowed to change the surcharges in different combinations and implicitly to modify the dynamic parameters of interacting system. For instance the natural frequency of the model of elastic structure at its own weight W = 50daN was f = 11Hz, at W = 100daN f = 6.1Hz, at W = 150daN f = 4.7Hz and finally at W = 250daN f = 3.4Hz (Fig. 5).

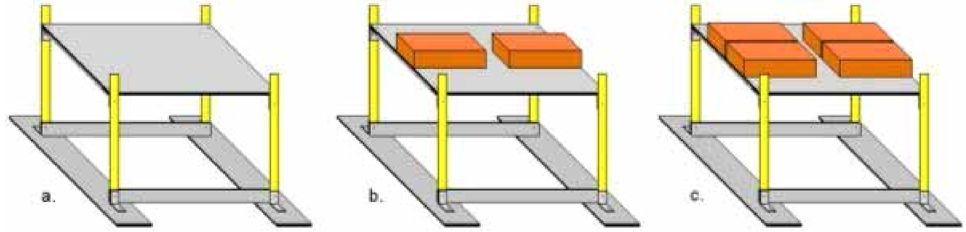

Figure 5: The model of elastic structure with one DOF and the surcharge

Separately, for supporting the recording devices another steel structure was provided (Fig. 6).

Figure 6: Installing the model with the elastic structure on the shaking table

Special attention was devoted to the collapse of retaining walls in order to define their ultimate limit states as analysis references (Fig. 7).

Figure 7: The elastic structure before and after collapse

Since the model of conventional walls was submitted to 52 shakes while the second to 57, for obtaining those 3,052 recordings in real time the electronic devices had to be kept under close monitoring. The principle used in processing the recorded data was that the volume of infill in the shear stack remained constant during tests. In the first step were analysed the two components of the motion in vertical and horizontal directions. Then, for sake of comparison the results were rectified (Figs. 8 and 9).

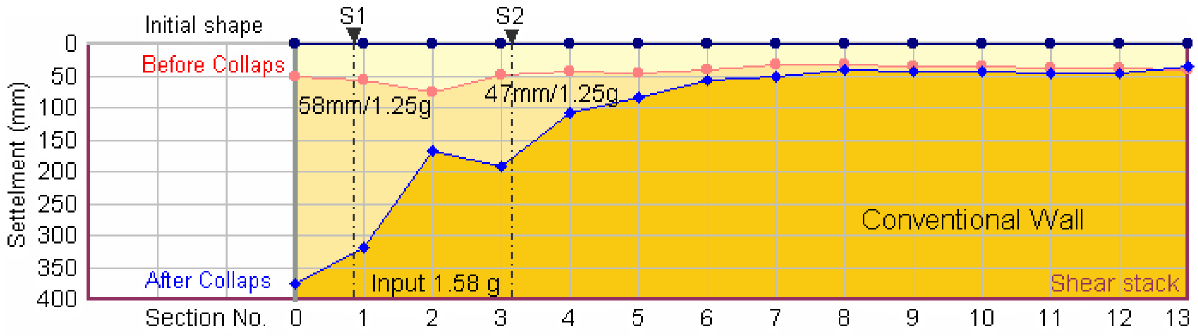

Figure 8: Rectified settlements in the model of conventional walls

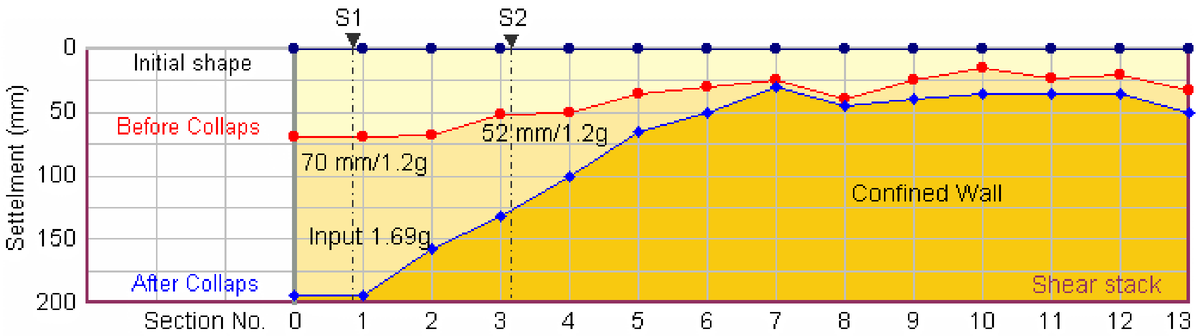

Figure 9: Rectified settlements in the model of confined walls

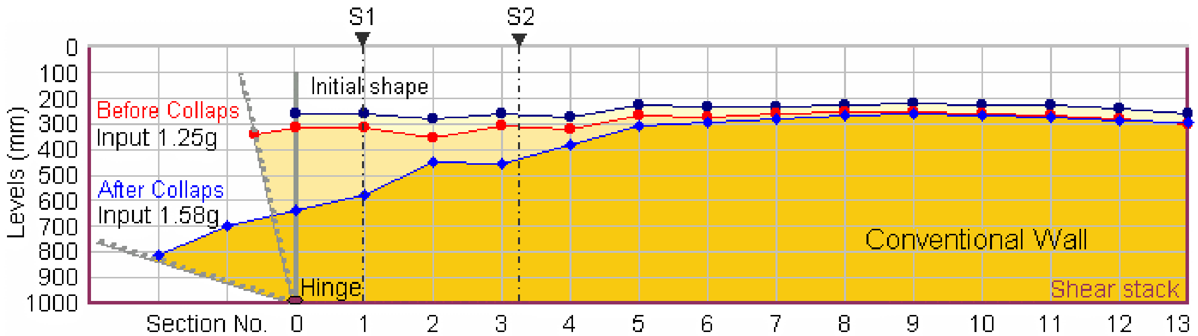

Figure 10: Horizontal displacements and settlements in the model of conventional walls

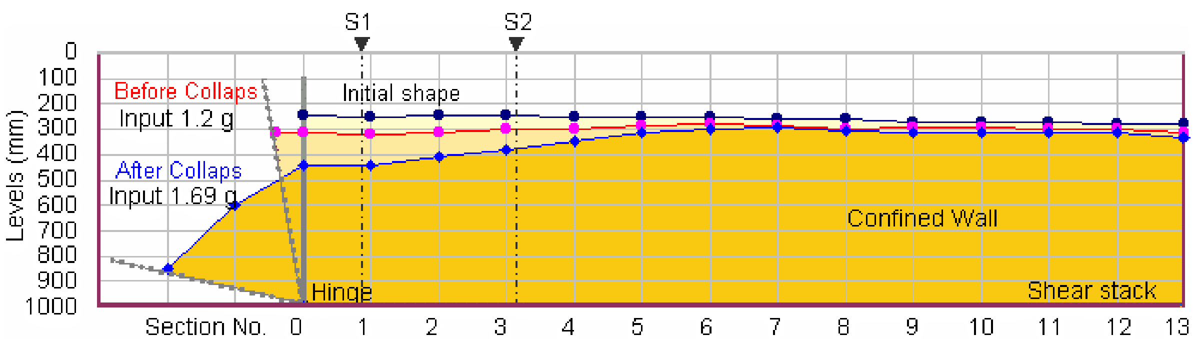

Figure 11: Horizontal displacements and settlements in the model of confined walls

One can see that in the case of conventional wall the collapse had a sudden and local effect, while in the case of confined wall the failure affected a large part of backfill and occurred gradually, with warning (Sofronie [8]). The real mechanism of collapse with elastic structure has shown that the assumptions provided by BS 8006:1995 are no longer valid for seismic actions (Figs. 10 and 11). That means Meyerhof hypothesis also loses its validity (Sofronie [9]).

FOURTH GENERATION OF MODELS

In order to draw out realistic conclusions, both programs were comparatively developed. It was compared the model of conventional retaining structures with the model of confined retaining structures. Both models were considered as prototypes. Unfortunately, constrained by the dimensions of existing facilities, both models had a limited height of only 900 mm. The results could not be transferred to full-scale retaining walls and, worse, no numerical models could be developed further in order to validate the tests for drawing practical conclusions. For the same reasons of reduced dimensions neither the pressure distribution under reinforced soil base nor the soil-structure interaction could be realistically investigated on shaking tables.

A box of 6m long, 2.5 m wide and 2.5 m high being suggested for use as a shear stack for a full-scale modelling of the reinforced-soil retaining walls. The stack is fixed on shaking table as to be easily moved in the commanded directions. For the model of conventional walls an aspect ratio of 0.6 is first adopted with a panel-facing. The model is checked with the aid of WinWall design program and uses as reinforcement geogrids Tensar SR55 accordingly arranged (Fig. 12-left).

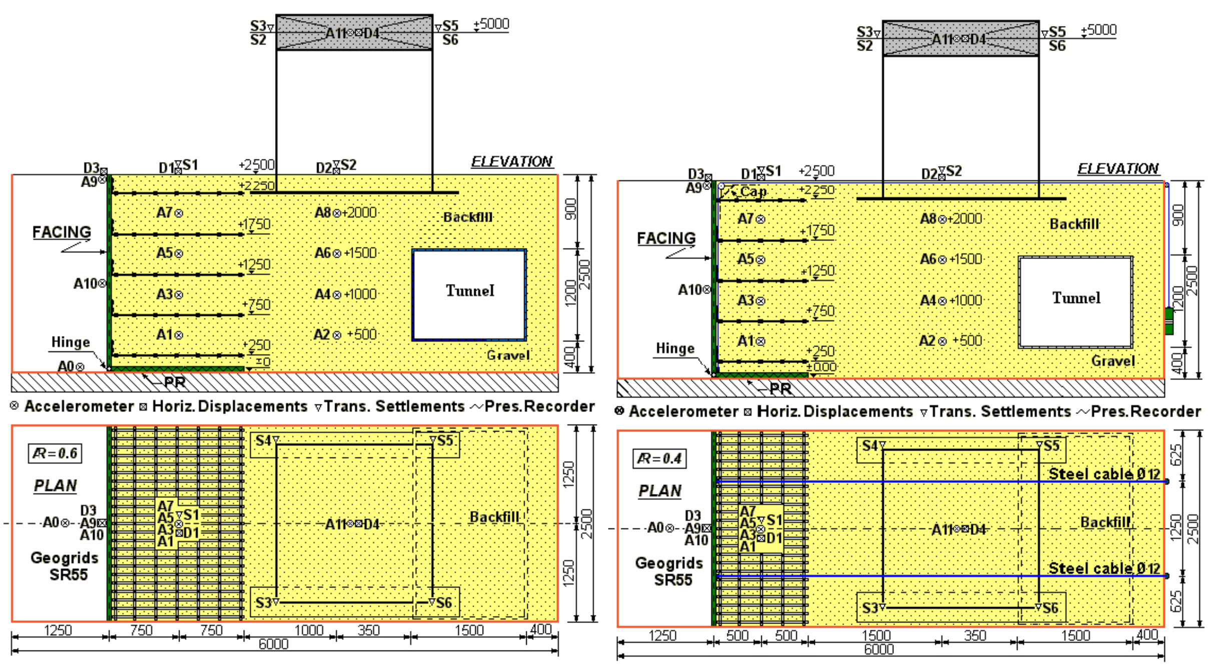

Figure 12: The pair of full scale models prepared for the new shaking table of Bristol University

The same shear stack is further easily reused for modelling the confined walls with an aspect ratio of 0.4 (Fig. 12-right). If well preserved the same reinforcement Tensar SR55 is accordingly adjusted. Two steel cables #12 are added for confining the reinforced soil structure. For permanent actions the retaining wall is supposed to be centred on its base. In all cases the confining degree remains under 20%.

The shear stack will be further used for searching the soil-structure interaction. Elastic structures with one or more degrees of freedom and with well determined natural frequencies will be located either over the infill or backfill of the two models. By recording their responses in settlements, horizontal displacements and accelerations, the dynamic behaviour of any elastic structure can be accurately simulated.

Obviously, the geometrical, mechanical and geotechnical characteristics of conventional and confined soil-structures can be properly adapted as requested by practical cases. The facing can be inclined or changed, while the hinge can be released or better fixed by clamping. The synthetic reinforcement can be also easily changed and the performances of new types of geogrids can be tested and validated. In order to fulfil all real conditions the gravel can be replaced with sand or any other granular material, with different degree of humidity or water-contents. Finally, the shape, inertia and stiffness of elastic superstructure can be designed according to practical interests and Eurocode provisions. For example, the influence of structural irregularities on seismic behaviour of buildings and structures can be thoroughly checked, as defined by EC8, The same box is further easily reused for modelling the confined walls with an aspect ratio of 0.4. If well preserved the same reinforcement Tensar SR55 is accordingly adjusted. Two steel cables #12 are added for confining the reinforced soil structure. For permanent actions the retaining wall is supposed to be centred on its base. As concerns the confining force it can be either kept constant or let variable and adapted to the horizontal actions.

TESTING PROGRAM

There are seven main objectives of practical interest as follows:

1. Settling phenomena of infill and backfill soils;
2. Horizontal displacements of facing and soil at different levels;
3. Response spectra of accelerations and dynamic behaviour with pointing out the amplifications and attenuations;
4. Distribution of ground bearing pressure under the facing base and check the validity of Meyerhof assumption;
5. Response to jerk and energy dissipation capacity of soil structures;
6. Soil-structure interaction for both conventional and confined types of retaining walls;
7. Comparative study between conventional and confined retaining soil structures.

None of above mentioned objectives have ever been searched on a full-scale model.

In accordance with testing objectives there would be necessary 6 Indikon transducers for settlements S1-S6, 4 Celesco transducers for horizontal displacements D1-D4, 11 Dytran accelerometers for response accelerations A1-A11, 1 Setra accelerometer for induced accelerations A0 and at least 4 elastic recorders for the bearing pressure PR1-PR4. The locations of the above mentioned devices are suggested as marked on figure 13. The laboratory can use any other available devices having the same functions.

For fulfilling objectives of the comparative testing program, as listed above, two degrees of freedom should be used, namely the horizontal displacement in the longitudinal direction of the models and the vertical displacements. The two DOF will be used separately and together in such combinations to cover the most severe of real cases. The types of input excitations will be established together with the technical staff of Research Centre in Earthquake Engineering in order to fulfil project objectives. Anyhow, the dominant input frequencies should be much lower than model natural frequency to avoid resonance occurring in the soil deposit. The span of testing program is extended on about 9 months after the EC funds become available. In the same period the validation of results by numerical analysis with the aid of UDEC 3.10 program is expected. A practical manual for the use of designers will be afterwards prepared

EXPECTED RESULTS

The proposed testing program is innovative beginning with the full-scale of retaining walls and ending with the seven objectives. Indeed, such a European project was necessary because so far advanced investigations were already carried out in other countries like Japan and Canada. The idea of using such a big shear stack is original and it has never been experienced before on a shaking table. With the aid of the same full-scale model, two different structural systems of reinforced soil with different aspect ratios will be comparatively checked.

Each of the seven objectives covers a distinct field of engineering problems. Therefore it is expected that the diagrams of settlements to show the difference in seismic behaviour between infill and backfill zones, the critical inputs for which sudden settlements might occur, arising stability problems and what happens along the interfaces between infill and backfill, where there are some geometrical and physical discontinuities. The diagrams of horizontal displacements present interest mainly for construction and stability of the facings. During earthquakes they are often displaced or tilted. Seismic behaviour of the four types of facings recommended by designers will allow assessing their safety factors. Some anchoring details deserve to be checked. The spectra of response accelerations are expected to show the phenomena of amplification or attenuation of the induced excitations. The location of inertial forces is also of high interest for seismic analysis and design of reinforced soil structures in accordance with the provisions of Eurocode 8.

The former tests have shown that due to geogrid reinforcement some layers of soil separately oscillate. This dynamic behaviour is dangerous and should be carefully checked on the full scale model. It is also expected from the same model to confirm Meyerhof's assumption regarding the distribution of ground bearing pressure under wall base. On this assumption are based several national codes and it is currently used in practice. The confining concept also uses Meyerhof's assumption and its accuracy might influence strongly dynamic phenomena. According to the 5th objective, it is expected the response of reinforced soil retaining walls to very short actions generated by explosions when the accelerations vary in time. It is of high interest to assess the soil-structure capacity to absorb and dissipate the induced energy. From soil-structure interaction the occurrence of phenomena of attenuation or amplification of the induced excitations is mainly expected. Finally, by summarizing the results, a comprehensive comparative study between conventional and confined soil structures could be drawn out. The expected results will be further used for solving three problems of high practical interest as follows: 1) Developing numerical analysis models with the aid of FLAC computing program; 2). Validation of the testing results obtained on smaller models on other shaking tables in Europe; 3). Checking some of the provisions of national and European codes used in design programs.

CONCLUSION

Retaining walls of reinforced soil proved to be an appropriate solution for preventing landslides caused by earthquakes associated with climate changes. The tests carried out on shaking tables have shown that soil structures are able to face very strong earthquakes suffering only minor and easily reparable faults. As for their ultimate limit state, they always occur gradually and with warning displacements, according to the principle of fail-safe. This ductile-like behaviour of soil structures is explained by their ability of avoiding local concentrations of stresses through spontaneous stress redistributions. Particularly, the confined soil structures, based on the state of three axial compressions, had shown much better behaviour when submitted to seismic actions. In order to elaborate realistic analysis methods and application technologies a testing program on full scale models should be completed by using two DOF. Besides soil-structure interaction, at surface and depth levels, the interlock of granular soil into geogrid apertures and the distribution of base-pressure should be carefully checked.

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