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Testing and modelling geogrid reinforced soil embankments subject to high energy rock impacts

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ABSTRACT: Geogrid reinforced embankments find application as barriers against rocks fall, for the protection of all kind of infrastructures, since they can absorb high quantity of dynamic energy from both cyclic and impulsive loads, with high resiliency and limited deformation. To study the behavior of geogrid reinforced embankments subject to high energy rock impacts, a large research program has been carried out by Politecnico di Torino University and Tenax Geosynthetics Technical Office (GTO), including both full scale tests, carried out in a specially built up facility, and extensive dynamic FEM modeling. Several geogrid reinforced embankments and unreinforced control embankments have been built and tested, both with single and repeated impacts, using different soil fills and kinetic energy levels. All the crash tests have been simulated through the ABAQUS/Explicit FEM code, which allows the evaluation of finite elements meshes in a 3-dimensional, dynamic, non-linear field using an explicit Euler solving algorithm. A first proposal for design criteria for reinforced embankment for rock fall protection ends the paper.

1 INTRODUCTION

Reinforced embankments are currently set up as barriers for rock fall protection, especially in those areas where the falling blocks are anticipated to have volumes or velocities great enough to break through the maximum resistance of traditional wire netting rock protection barriers (Lazzari et al., 1996) or when dealing with large “target” infrastructures as mountain highways, railways and inhabited areas .

Apart from the better performance in terms of protection efficiency, among the advantages that a reinforced embankment can present in comparison to a high-energy absorption wire netting, mention can be made of:

- the efficiency of the protection in the case of repeated impacts along the same slope section;
- reduced maintenance;
- reduced environmental impact, which becomes especially important when large extensions are required to protect inhabited areas or road infrastructures;

On the other hand, the negative aspects that can be mentioned are:

- important area occupation, because the base of the barrier increases as the height of the barrier increases;
- planimetrical and altimetrical characteristics of the territory have to be suitable for the construction of the reinforced embankment.

Furthermore, whenever geogrids are used as reinforcing elements, the following advantages are also introduced:

- the soil is “tied” by the geogrid both in the longitudinal and transversal directions of the reinforced embankment, thus increasing the resistance of the structure;
- HDPE geogrids have an elastic-plastic behavior so that they quickly react to applied loads with an increase in the elastic modulus; in the case of short term impact loading, creep phenomenon does not occur, therefore the whole tensile resistance of the geogrid can be mobilized;
- geogrids allow an increase of the dynamic dumping characteristics of the reinforced soil compared to unreinforced soil, both through the energy that is directly absorbed by the geogrid itself and through the “Coulomb dumping”, due to friction generated in the dynamic stage (Carotti and Rimoldi, 1998).

It has to be pointed out that design regulations for reinforced embankments subject to dynamic impact are still rather vague as very few specific researches on the subject are available and no analytical formulation has been proved to be solid enough to provide designers with a simple and feasible evaluation of the phenomenon.

2 FULL SCALE TESTS

2.1 *Test Program*

Following the experiences acquired in the full scale testing of reinforced embankments with impacting rock blocks (Burroughs et al., 1993; Yoshida, 1998), a new program of crash tests had been set up in the Meano test site (near Trento, Northern Italy) (Fig.1) which was specifically set up for testing rock fall protection devices (Peila, 1999; Rimoldi et al. 1999).

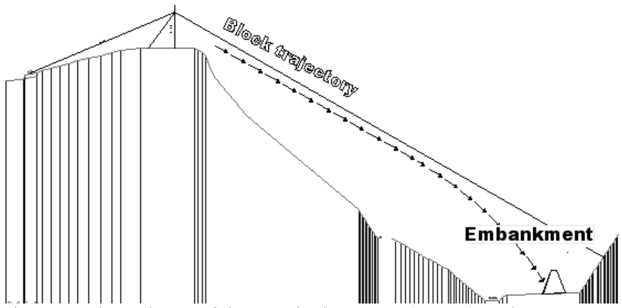

Fig. 1: Section scheme of the test site in Meano (Trento), Italy.

In this particular testing facility, blocks are accelerated while guided by a special trolley, sliding on steel wires, and then dropped to reach the target with a free flight parabolic trajectory; therefore, by using different target positions and boulder sizes, a wide set of energy levels is available for full scale tests.

All impacts have been video recorded at frame rate of 25 fps using Beta cameras with time code, which allowed to verify the final impact speed, first evaluated through simple energy calculation, and yielded, at the same time, information about the order of magnitude of the contact time.

The program of carried out tests, summarized in table 1, features the following experiences:

- test 1: 4.2 meters high wall, type 1 soil (see table 2), reinforced with TT050 geogrids, tested at an energy level of about 2500 kJ;

- test 2: 4.2 meters high wall, type 1 soil, reinforced with TT045 geogrids, tested by three impacts, each one developing an energy level of about 4500 kJ;
- test 3: 4.2 meters high wall, type 1 soil, without any reinforcement or steel grid formworks, tested at an energy level of about 4500 kJ;
- test 4: 4.2 meters high wall, type 1 soil, reinforced with TT045 geogrids, without steel grid formworks, tested at an energy level of about 4500 kJ;
- test 5: 5 meters high wall, built with low quality soil filling (type 2 soil), reinforced by TT045 geogrids, tested by two impacts developing about 4500 kJ each.

Table 1 – Summary of the performed tests

Number	Energy [kJ]	Impacts	Formwork	Geogrids*	Soil*
1	2500	1	Yes	TT050	Type 1
2	4500	3	Yes	TT045	Type 1
3	4500	1	No	No	Type 1
4	4500	1	No	TT045	Type 1
5	4500	2	Yes	TT045	Type 2

*see tables 2 and 3 for details

Table 2: Geotechnical parameters for each tested soil fill

Soil	c' [KPa]	ϕ' [°]	γ'[KN/m^3]*
Type 1	9	34	21.10
Type 2	50	30	17.97

*after compaction

The reinforced embankments built for tests number 1 to 4 were designed with isosceles section of 4.20 m in height, the upper base was of about 1.00 m and the lower base about 5.00 m; in test number 5, slightly steeper faces (about 70°) were realized so that, having a wider base span, the tested wall was about 5 meters high, with a top width of about 1.2 meters. The inclination of the faces was kept equal on the two sides, in order to test an embankment with the smallest cross section possible (fig. 2).

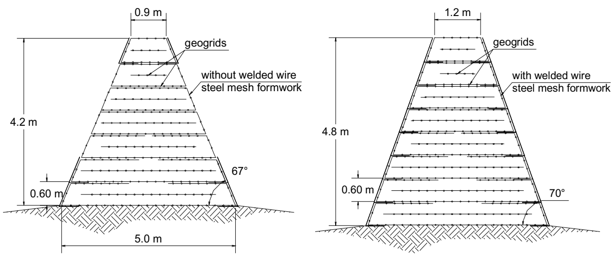

Fig. 2: Sketched cross section of the embankments built for test 4 and 5.

The soil used as fill was, for tests from 1 to 4, found at the test site, while in test number 5 an embankment made out of reinforced sandy clay was tested, in order to evaluate the influence of weak soil characteristics on impact resistance.

High-Density Tenax polythene geogrids (TT050 Samp and TT045 Samp) were used as reinforcements; such geogrids are 100% HDPE extrusion produced, have high mechanical resistance and are stabilized to the action of UV rays thanks to carbon black. The main parameters about soil and geogrid layers, both acquired through laboratory testing, are given in Tables 2 and 3.

Table 3: Geogrid layers parameters

Parameter	Value	
2% elongation resistance	11	KN/m
5% elongation resistance	25	KN/m
Maximum tensile stress (TT 50)	50	KN/m
(TT 45)	45	KN/m
Yielding strain	11.5	%
Long term resistance	19	KN/m

Two different concrete smooth-edged cubic boulders, respectively weighting about 5 and 9 tons, have been used for crash tests, both impacting with the same speed of about 30 m/s.

2.2 *Test Results*

2.2.1 *First test*

Block's speed at the moment of the impact was estimated as 31.73 m/s, therefore the kinetic energy developed at the moment of contact is about 2511 kJ.

The impact occurred in a high portion of the reinforced embankment, where the transversal thickness was about 1.2 m. The maximum measured displacement on the opposite side was about 0.23 m and it was concentrated or rather confined by the reinforcements on the two layers of the embankment involved in the impact (fig. 3).

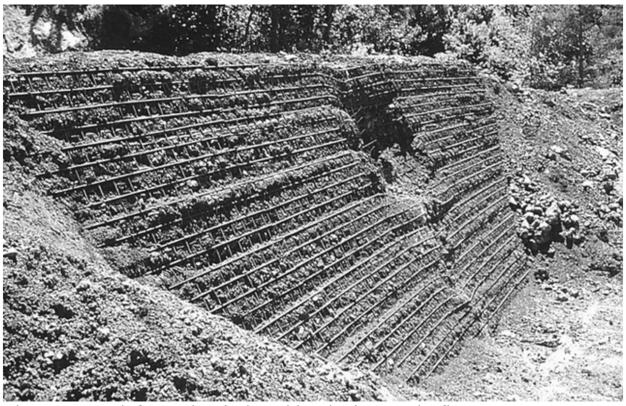

Fig. 3: Front deformation induced by the impact in first test.

After the test, the reinforced embankment was dug and a tension crack was observed (fig. 4); the joint began 0.60 m below the top and then spreading inside downward almost following the shape of the boulder. In the maximum opening position, the tension crack has a width of about 140 mm (comparable, as order of size, with the extrusion below the reinforced embankment). No geogrid appeared to be broken.

Fig. 4: The tension crack as observed after the first test.

2.2.2 *Second test*

Translational velocity of the boulder at the moment of the impact was estimated as 31.3 m/s, therefore the kinetic energy of the block at the moment of contact is about 4354 kJ.

The reinforced embankment was not pierced and the occurred deformations did not cause any structural collapse. On the front side a crater was formed with a maximum depth of about 1 m while on the back-side a large displacement of soil (about 0.90 m) could be observed. The geogrids have occasionally been thorn, but the global stability of the structure appeared to be assured anyway.

The global behavior of the reinforced embankment showed a major influence of the geogrid interfaces, which allowed a relative sliding of the layers involved by the impact.

After other two crash tests, each one developing about 4300 kJ, it was shown that such a barrier can stop up to three high energy boulders before collapsing because of failure of reinforcing layers and massive loss of compaction in the soil medium

2.2.3 *Third test*

The purpose of the third test was to evaluate the behavior of a steep-sided, unreinforced embankment under a heavy energy impact. To achieve the proper slope of the embankment faces, strong compaction of the soil has been performed, and the test has been carried out right after finishing the construction phase (thus exploiting the soil resources in the short term period under undrained conditions). Apart from the geogrid layers absence, the test followed the same geometrical characteristics of the ones presented above, so that the same impact energy was achieved.

As expected, the whole structure collapsed right after the impact, but the block was arrested by the embankment, stopping its flight after penetrating inside the front face for about 1.5 m. Deformation measuring was impossible due to the collapse of the fill (fig. 5).

Fig. 5: Side view of the impact during the third test.

2.2.4 *Fourth test*

The aim of the fourth test was to evaluate the influence of steel mesh formwork on embankment's global behavior. To have a term for comparison, the embankment was kept identical to test 2, but formworks were removed right before the test.

After the impact, in which the boulder was successfully arrested, a crater with a maximum and minimum depths respectively of 0.90 and 0.50 m was measured, while the back deformation showed displacements of about 1 meter in the third layer from the top. As foreseen by numerical models, an upward displacement of the top layer was observed.

Geogrids wrapping of layers 3 and 4 (from the top) were pulled out, thus allowing large deformation in the face soil to take place. Furthermore, comparing front crater size and back displacements, it's easy to notice a big volume difference due to large tension cracks, only partially showing up on the surface, which opening is related to the lack of reinforcement induced by geogrid pull-out.

2.2.5 *Fifth test*

In this test, a slightly weaker soil fill was used for the embankment construction, in order to evaluate the role of soil plasticity and resilience both in the impact and post-impact phase. A slightly different embankment was set up, with 70° slopes, 1.2 top width, and 8 geogrid layers (7 actually exposed to the impact and 1 buried in the construction debris).

The boulder was successfully arrested and penetrated the front face causing a large crater with a maximum depth of about 2 meters, involving 4 soil layers. On the back face, a maximum displacement of 0.80 m was measured. Two shear cracks in the impact direction showed up on the top layer as results of the upward displacement but, after the block was removed, the reinforcements effect allowed it not to collapse inside the impact crater.

3 NUMERICAL MODELLING

Several numerical models have been developed in order to get a better comprehension of the behavior both of reinforcement layers and soil fill and a more careful analysis of the various kinematics involved in the impact phase; the process of course involves parametric adjustments according to the results observed during the full scale field tests discussed in the previous paragraph.

All the analyses have been performed by the Politecnico di Torino University, in the Tunnel and Underground Space Center laboratory (TUSC), with the ABAQUS/Explicit (Hibbit, Karlsson & Sorensen, 1998-2001) Finite Elements software; using an explicit Euler algorithm, this numerical package allows the simulation of three-dimensional, dynamic phenomena, taking into account the aspects related both to non-linear behavior and the large displacements typical of this impact problem.

Soil has been modeled using 8-node linear bricks controlled by the modified Drucker-Prager elastic-plastic criterion, which parameters have been fitted with the Mohr-Coulomb data of the original soil. On the basis of field observation, geogrid layers have been simulated through 4 node shell elements with perfectly elastic behavior, while the impacting boulder has been supposed to be infinitely stiff; the program solves contact problems for geogrid interfaces and boulder impact using a penalty algorithm; best fitting to the experimental full scale data has been reached with a friction angle of about 21°, meaning that the whole slipping kinematics is controlled by large strain, residual surface behavior.

According to the results of the numerical simulation of test n.2, the following observation can be pointed out:

- the layered structure heavily influences the overall behavior, so that only the layers involved in the impact show important horizontal displacements (fig. 6);

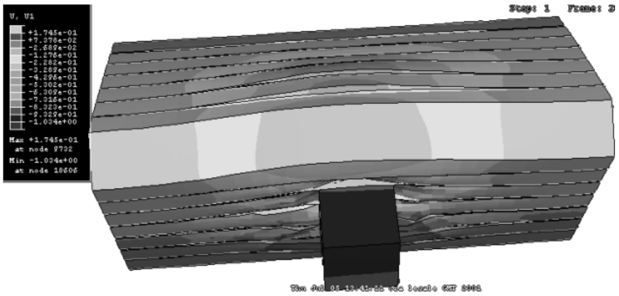

Fig. 6: Deformed rendering of the model, simulating the test n. 2.

- looking at the displacement vectors (fig. 8) and at geogrid stresses (fig. 7), the top most layers show an upwards acceleration because of the effect of the spherical wave front of the energy produced by the impact;

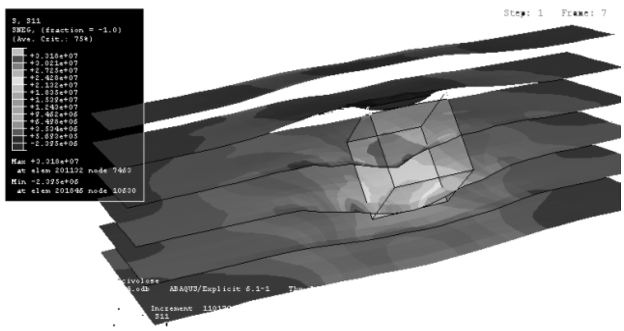

Fig. 7: In-plane stress traction stress distribution on geogrids.

- analyzing geogrid data, high tensile in-plane stresses show up in geogrids n 4 and 5 (closer to the impact area) right after the boulder arrest (0.12 sec); these stress components are of the same order of magnitude of the tensile strength of the geogrids; hence the fact that geogrids didn't break during tests validate the hypothesis of perfectly elastic behavior and of increased dynamic strength and modulus (not quantified yet).

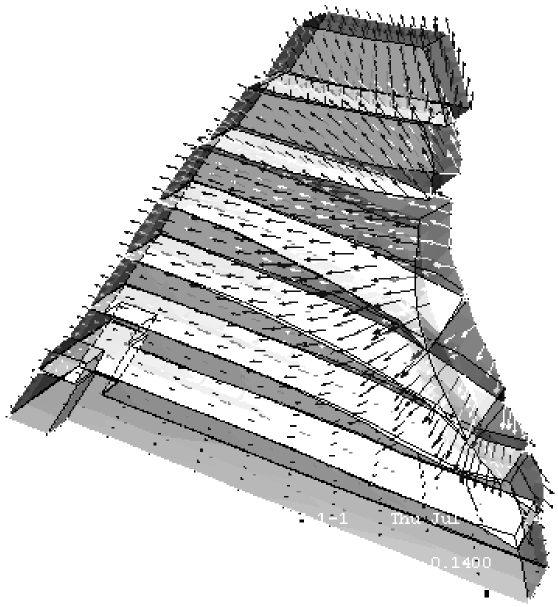

Fig. 8: Displacement vectors in the cross-section after 0.12 s.

4 DISCUSSION AND DESIGN SUGGESTIONS

It is quite evident that reinforced embankments subject to high energy rock impacts cannot be tested with reduced scale models, since it would be impossible to reproduce all the phenomena that occur in a fraction of a second. Being the impact an impulsive action in nature, the falling rock transfers to the embankment the momentum and the angular momentum of the motion. The impulsive force that is instantly applied to the embankment depends on the mass, the shape and the velocity of the rock, and on the mass, geometry, geotechnical properties, construction method of the embankment.

Moreover the response depends on the number, position, lay out and technical characteristics of the reinforcing geosynthetics. It results practically impossible to find the laws for reducing the scale of all these parameters. Hence the only way to study the behavior of reinforced embankments subject to high energy impacts is to perform full scale tests. These require complex logistics and very high costs. That's why the research herein presented is the first one of its kind in the world. Due to the high costs, the number of tests had to be limited to five. Nevertheless the test program includes two practical situations in terms of one soil of very good geotechnical characteristics, and one frictional-cohesive soil; plus a control embankment without reinforcement.

Moreover impacts with two blocks (5 ton and 9 ton) have been applied, resulting in 2500 kJ and 4350 kJ impact energy; repeated impacts on the same embankment have been performed as well. The continuous monitoring of the impacts through multiple high speed video cameras is essential for understanding what happens in each test, and to provide suitable data for the development of realistic numerical models. Even with a powerful 3-D FEM software like ABAQUS, anyway, there are problems in reproducing all the phenomena that have been observed.

Nevertheless the collected data has allowed the development of a sophisticated FEM model, which results very useful for analyzing the stresses, strains, displacements, and forces that are generated by the impacts. Only the unreinforced embankment, which has been built with extreme care in order to get the stability at 60° slopes just for the very short time (1/2 hour) required to perform the test, couldn't be satisfactorily reproduced by the FEM model.

Therefore, it is difficult to quantify the effects of reinforcement, but tests show that a properly reinforced embankment can resist several high energy impacts without failure, while an unreinforced one would need a much larger cross-section and gentle slopes, resulting in large plane area required. The tests results and the FEM models yield some interesting features:

- The energy wave generated by the impulsive force applied to the embankment propagates in a quasi-spherical shape.
- This means that below the rock imprinting in the front face the soil is highly compressed, while above the imprinting the soil is subject to upward vertical stresses, which lift the top layers and decrease the normal stresses on the reinforcement, thus decreasing also the shear stresses at the interfaces.
- The soil mass adjacent to the rock imprinting results in compression, while soon after the acceleration applied to the soil mass produce an outward horizontal movement, equivalent to a tensile force being applied to the soil; at the limit between the compressed and the "tensioned" zone tension cracks are formed; the soil mass is therefore separated in two parts, and only the tensile resistance of the reinforcement can avoid the failure due to outward displacement.
- The FEM model clearly shows that geogrids are able to "canalize" the energy, so that the initial spherical shape is soon converted into a horizontal cylinder; outward displacements occur within this cylinder, leaving the remainder of the soil mass practically in place.
- The FEM model also shows that the stresses in the geogrids have an important component in the direction parallel to the length of the embankment: this justify the design assumption of putting geogrid layers also in such direction.
- Both tests results and FEM models confirm that geogrid are subject to high tensile forces, almost reaching the tensile resistance of the geogrids actually used; but the impulsive nature of the active force allows to not consider at all any creep effect, and to consider a higher dynamic tensile modulus of the geogrid than the static one. Geogrids with 50 – 70 kN/m ultimate tensile strength and 25 kN/m tensile strength at 5 % strain, placed at 0.60 m vertical spacing, seems adequate for a 5 m high embankment subject to 4500 kJ impacts.
- Repeated impacts produce larger and larger outward displacements, which can bring to the pullout of the wrapping length of the geogrids; hence this length shall be designed much longer than in static conditions; connection of the front face and back face wrapping length is highly suggested.

5 REFERENCES

Burroughs, D.K. & Henson, H.H. & Jiang, S.S. 1993. Full scale geotextile rock barrier wall testing, analysis and prediction, *Geosynthetics* 1993, Vancouver : 959-970.

Carotti, A. & Peila, D. & Castiglia, C. & Rimoldi, P. 2000. Mathematical modelling of geogrid reinforced embankments subject to high energy rock impact, Eurogeo, II *European Geosynthetics Conference and Exhibition*, Patron Bologna: 305-310.

Carotti, A. & Rimoldi, P. 1998. Parametric study for geosynthetic reinforced walls under sustained earthquakes, *Sixth International Conference On Geosynthetics*, Atlanta, Georgia (USA): 25-29.

Peila, D. & Castiglia, C. & Oggeri, C. & Guasti, C. & Recalcati, P & Sassudelli, F. 2000. Full scale tests on geogrid reinforced embankments for rockfall protection. Eurogeo, II *European Geosynthetics Conference and Exhibition*, Patron Bologna: 317-322.

Recalcati, P. & Oggeri, C. & Castiglia, C. 2001. Linee progettuali per rilevati paramassi. International Symposium *Opere di difesa da Caduta Massi*, Siusi (BZ), GEAM Torino: 89-100

Yoshida, H. 1999. Recent studies on rockfall control in Japan, Joint Japan-Swiss Scientific Seminar on *Impact Loads by Rock Falls and Design of Protection Structures*, Kanazawa, Japan.

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