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Full-scale impact test on a reinforced earth embankment with advanced monitoring for rockfall protection

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Abstract

Reinforced earth embankments represent a robust solution for rockfall mitigation, yet their dynamic response under high-energy impacts remains poorly documented. This study presents a unique full-scale impact test performed on a 6.54 m-high RPE composed of nine layers of granular material reinforced with Green Terramesh units by Maccaferri, developed in the framework of PERSEIDI project (contributo Legge 6/99 Provincia Autonoma Trento - CUP:C39J21046780001). The test involved a standardized block (EAD 340059-00-0106:2018) impacting below the first reinforcement layer with an energy of approximately 10 MJ, simulating an extreme rockfall event. The novelty of this work lies in the advanced multi-sensor monitoring system integrated into the embankment and in the block. The embankment was instrumented with tri-axial and mono-axial accelerometers positioned across different layers, both at the impact centre and laterally to the impact zone, to capture the propagation of dynamic loads and the volume of disturbed material. A custom-designed network of strain gauges was embedded within the reinforcement layers to monitor tensile forces, while load cells at the foundation recorded stress transmission during the impact. Additionally, the impacting block was equipped with a gyroscope and accelerometer to track its kinematics. High-speed cameras captured the impact sequence, enabling correlation between visual observations and sensor data. Preliminary results reveal the extent of the volume of the embankment disturbed by the impact. The combined dataset provides unprecedented insight into energy dissipation mechanisms and deformation patterns in reinforced earth structures under extreme impacts. This experiment establishes a benchmark for validating numerical models and improving design guidelines for embankments used asrockfall protection systems. The integrated monitoring approach offers a powerful tool for understanding structural resilience and optimizing reinforcement strategies under high-energy impact scenarios.

Keywords

Rockfall protection embankment, Impact test, Monitoring.

1 Introduction

Rockfall events are natural phenomena that can expose infrastructure and human life to significant risk if not adequately protected. Among protective measures, rockfall protection embankments (RPEs) built using reinforced earth (RE-RPEs) represent a suitable solution (Marchelli and Deangeli 2022), especially in cases of high energy levels, where other types of structures (e.g. rockfall barriers) cannot withstand the impact, or, due to their low maintenance requirements, in areas subject to frequent events.

Unfortunately, the structural response of these works under impact loading has not yet been completely investigated or fully understood, mainly due to the limited number of full-scale tests available in the literature. Peila et al. (2007) and, subsequently, Mongiovì et al. (2014) tested RE-RPEs reinforced with HDPE geogrid systems at energy levels of 4200 kJ and 6600 kJ, respectively.However, nowadays these energy levels are typically addressed by rockfall barriers, while RE-RPEs are generally employed for impact energies greater than 10000 kJ.

In this work, an innovative impact test, developed within the framework of the PERSEIDI project, was carried out on an RE-RPE, reaching an impact energy of approximately 10 MJ, representing the highest-energy test performed worldwide on this type of structure. The RE-RPE was built using the Green Terramesh reinforcing units (Fig. 1a) described in Section 1.1with a trapezoidal cross-section, a height of 6.54 m, a crest width of 2.0 m, and faces angles of 67° (Fig. 1b). A cableway system was used to reproduce the impact, and the details of the test setup are reported in Section 2.The innovations of the test consist on the energy level and anadvanced multi-sensor monitoring system, which included a standalone device to record acceleration and angular velocity within the impacting block, together with a 32-channel data acquisition system used to record accelerations at several points of the embankment, dynamic forces at selected points of the foundation, and strain state in the reinforcements. Further details are reported in Section 2.

The test results highlight the resisting mechanisms of the Green Terramesh reinforcing units, together with the capability to record significant physical quantities that are fundamental for understanding the behaviour under impacts of RE-RPEs and to be used as benchmark data in numerical model validation.

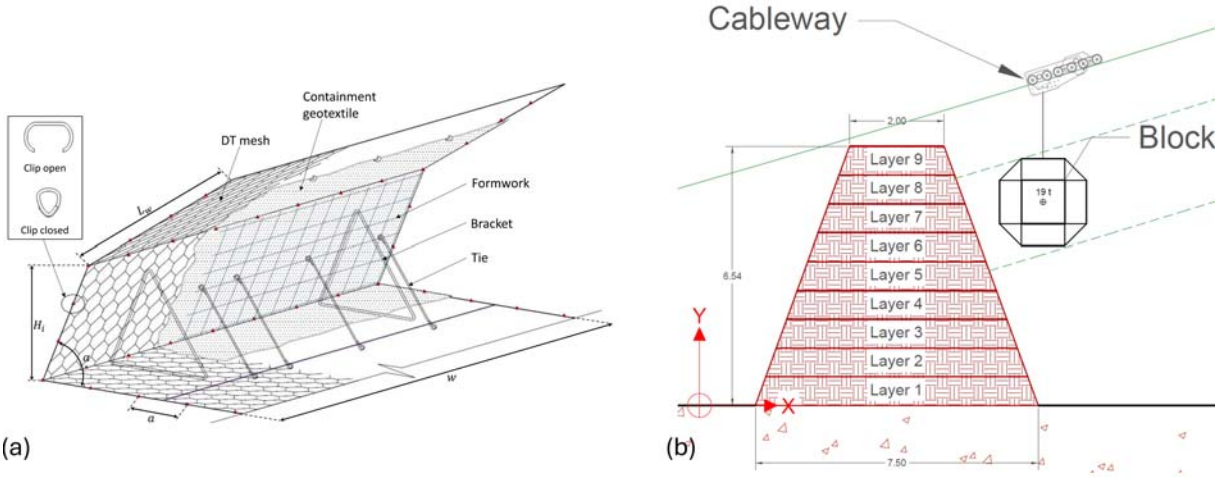


Fig. 1 (a) Terramesh system; (b) RE-RPE cross section of the test and test set-up.

1.1 Green Terramesh reinforcing units

The Green Terramesh Light is a preassembled modular system used to build reinforced soil structures with an inclined vegetative face; the units are manufactured from a continuous element of double twisted (DT) wire mesh, mesh type 8x10, with a polymer (Polimac) coated steel wire having a diameter of 2.20/3.20 mm. All the Green Terramesh Light units adopted for the RE-RPE are 3 m long (Fig. 1a). According to ETA No. 16/0758 (2020), the mesh has a tensile resistance of $F_{max} = 40 \pm 5\ kN/m$ at the strain of $\varepsilon = 10\%$, as reported by thetechnical datasheet. Rectangular electro-welded steel meshes (15×15 cm, Ø8 mm, B450C) are installed on the RE-RPE side banks as formwork purposes and are coupled with the DT reinforcing element through steel clips. The clips, according to EAD 200086-00-0602, have a characteristic strength of 2 kN and are also installed along the boundaries between adjacent Green Terramesh Light elements, acting as joints, with a spacing of 20 cm.

2 Test and monitoring system

The RE-RPE was built according to the typical construction procedure adopted for reinforced-earth works. The compaction method was calibrated on the first layer to achieve a minimum dry soil density equal to 95% of the Proctor value. The soil employed was a local material consisting of 65% gravel, 25% sand, and approximately 10% silt, and its mechanical properties were assessed through large-scale direct shear tests. In particular, the tested samples included a maximum grain size of 30 mm, resulting in cohesion of 36 kPa and a friction angle of 40°. Consequently, the material used during construction was sieved at 30 mm to ensure consistency between the laboratory-derived mechanical parameters and the in-situ material properties.

Plate load tests, performed in accordance with CNR BU No. 146 (1992), were carried out during construction to assess the stiffness parameters of the RE-RPE. The first deformation modulus values obtained were as follows: two tests on the foundation yielded values of 52 MPa and 50 MPa; for the overlying layers, Layer 1 showed 18 MPa, Layer 2 showed 19 MPa, Layer 3 showed 18 MPa, Layer 5 showed 26 MPa, and Layer 7 showed 15 MPa. Moreover, during construction, the sensor network described in Section 2.1 was installed.

The test consisted of launching a standard polyhedric block, in accordance with EAD 340059-00-0106:2018, against the upstream side bank of the embankment. The block had a mass of 18822 kg and an external size of 2.08 m, resulting in an average computed density of 2952 kg/m³. The block was launched leaving the upper layer (Layer 9) unaffected by the impact, as typically assumed in RE-RPE design under impact conditions, with an impacted height measured from the foundation to the centre of the impacted area of approximately 4.72 m. The impact energy was achieved by imposing a difference in elevation along the cableway and launching the block suspended from a trolley; before impact, the block was released to allow free parabolic motion.

The RE-RPE was designed to approach near-collapse conditions under an impact energy of 10 MJ, consistently with the collapse-based design approach under impact conditions proposed in recent literature (Vigna, 2025; Vigna et al., 2025). The design was carried out using a numerical approach based on Abaqus/Explicit, following the modelling strategy described in Vigna (2025), which resulted in the cross-section shown in Fig. 1b. The numerical model was fundamental for estimating the expected magnitude of the physical quantities to be measured and, consequently, for selecting appropriate sensors, thereby avoiding issues related to signal saturation or insufficient measurement resolution.

2.1 Monitoring system design

The physical quantities considered fundamental for a proper understanding of the behaviour of the RE-RPE subjected to impacts werethe forces acting on the foundation, the accelerations within the soil layers, the strain state of the reinforcements, and the three-dimensional deformed shape. Regarding the impactor, the block deceleration was considered the most important parameter to be measured, as it reflects the global structural response of the system.

A standalone acquisition system was selected to measure the deceleration and angular velocity of the block (Set 1), together with a 32-channel acquisition system used for the sensorswithin the RE-RPE (Set 2). The outputs of the previously mentioned numerical model were used to define the required sensor specifications, which are listed in Table 1. The test was recorded using 3 high-speed cameras, one of which was installed perpendicular to the block trajectory at the impact location in order to measure the impact velocity. In addition, the RE-RPE geometry was surveyed before and after the test using LiDAR techniques, allowing the reconstruction of the complete three-dimensional shape with an accuracy of$\pm 1\ cm$.

2.1.1 Instrumentation set-up

The selected instrumentation chosen on the market is reported in Table 1. The installation of the sensors required a dedicated design in order to prevent damage to the measurement system and issues in signal acquisition. Fig. 2 shows some of the adopted arrangements.

Table 1. List of instruments required for the monitoring network planning and the ones selectedfor measures on the block (Set 1) and those on the RE-RPE (Set 2).

Instrument	**Number**	**Minimum specification**	**Model**
		Set 1: measures on the block	
Triaxial accelerometer	1	$\pm 100g$	ASC 5521MF-200-25A
Triaxial gyroscope	1	$\pm 10 rad/s$	ASC 273-075-6A-9L3
Data recorder	1	1s	DATABRICK3
Acquisitor stand alone	6 channels	10 kHz	
		SET 2: measures on the RE-RPE	
Displacement sensor	2	$\pm 25mm$	PS-C15M
Strain gage	6	$\pm 1\%$	ID/KFGS-1-350-C1-11
Load cell	3	$> 500\ kPa$	FTF01-PTC100kN
Triaxial accelerometer	6	$\pm 100g$	ASC 5521MF-200-25A
Monoaxial accelerometer	3	$\pm 100g$	ASC 4421MF-200-25A
Data recorder	1	5s	CronosFlex2000
Acquisitor	32 channels	40 kHz	

The entire Set 1 was installed in the block by means of a stiff steel box rigidly fixed to the block. This solution ensured an appropriate coupling between the sensor box and the block, allowing accurate recording of block vibrations; additionally, a dedicated design was adopted to minimize noise and unwanted vibration effects (Fig. 2a).

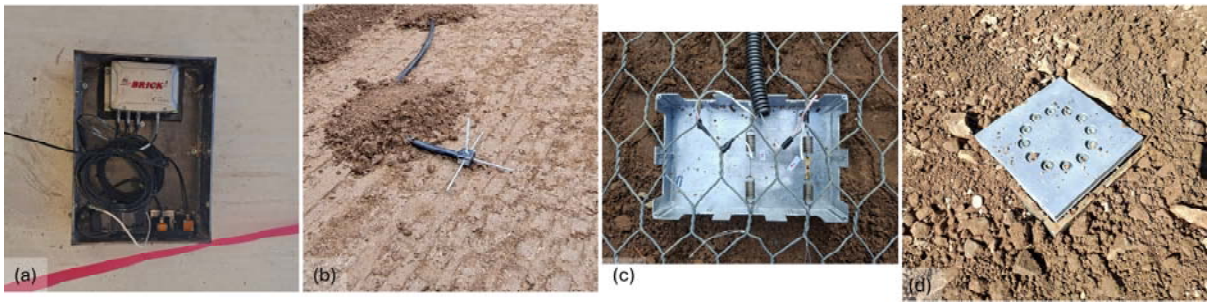


Fig. 2 Some arrangements of the sensors adopted for the impact test: (a) sensors on board of the block (accelerometer, gyroscope and stand-alone acquisitor); (b) accelerometer embedded in a layer of the RE-RPE; (c) device used to measure the strain state on the reinforcement; (d) load cell on the foundation.

The accelerometers of Set 2 were evenly distributed among the embankment layers and were always installed at mid-height of each soil layer. Each accelerometer was protected by a metal box and rigidly connected to the soil through steel bars (Fig. 2b). The strain state of the double-twist mesh was measured using a dedicated device developed and described in Vigna (2025). This device is based on a system of springs connected to the mesh hexagon, which induce deformation in a strain-gauged plate; knowing the relationship between spring displacement and strain, the local strain of the DT mesh can be derived.

Finally, the additional dynamic normal forces acting on the foundation were recorded by three load cells installed at different locations along the foundation. The load cells were housed in steel boxes, with their upper surfaces positioned at the level of the first embankment layer.

A sampling rate of 40 kHz was set for the Set 2 acquisition system. This value was selected considering the spacing between sensors, the wave propagation velocity in the medium, and the required temporal resolution of the measurements.

3 Preliminary test results

The block impacted the structure along its axis of symmetry at a height of approximately 4.72 m, measured from the foundation plane to the centre of the impacted area, leaving a freeboard of about 0.73 m. The high-speed camera located perpendicular to the impact point (frame rate 3000 fps),measured a velocity at the impact of 32.87 m/s, with an inclination angle with respect to the horizontal of 21.18°, resulting in an impact energy of 10168 kJ.

Fig. 3 shows a comparison of the upstream side bank of the RE-RPE before and after the impact. Fig. 3b clearly highlights that the block impacted exactly at the centre of a Green TerrameshLight module, which had been installed in a stacked (i.e. non-staggered) configuration and symmetrically with respect to the side banks.

From a macroscopic point of view, the observed mechanical response consisted of the formation of discontinuities along the boundaries of the Green Terramesh Light modules, extending from the base of the affected layer up to the crest, while the external portions of the embankment appeared to be almost unaffected. This observation is confirmed by the cross-sections obtained from the LiDAR survey and shown in Fig. 4. The cross-section along the symmetry axis of the impact shows a maximum downstream displacement of approximately 1.75 m, associated with an upstream deformation of about 1.0 m. Moving with the sections outwards, in correspondence of the Green Terramesh Light boundaries (Fig. 4b) the displacement field can be considered to remain constant, instead passing in the following section (Fig. 4c) the displacement field drops.

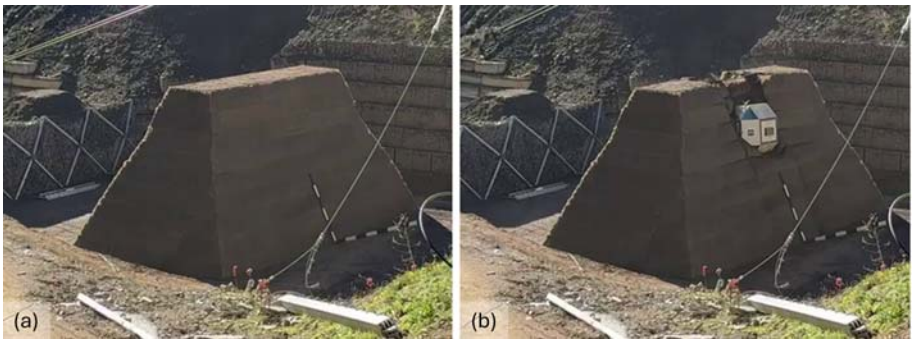


Fig. 3 Upstrem side bank of the tested RE-RPE before the impact (a) and after the impact (b).

The block remained embedded within the embankment, and the structure is self-standing, without reaching global collapse. However, limited soil leakage phenomena were observed on the downstream side bank.

Overall, both monitoring systems successfully recorded the target physical quantities. Only a limited number of accelerometers installed within the RE-RPE showed signal saturation, likely due to their proximity to the impact front. Fig. 5 a reports the acceleration components recorded on the block, showing a proper functioning of the measurement set-up. In particular, the highest acceleration component was recorded along the impact direction (x-direction), with a peak value of approximately 50 g. The maximum computed resultant acceleration was 53.42 g, with an impact duration of about 0.10 s, resulting in an estimated impact force of approximately 11.5 MN.

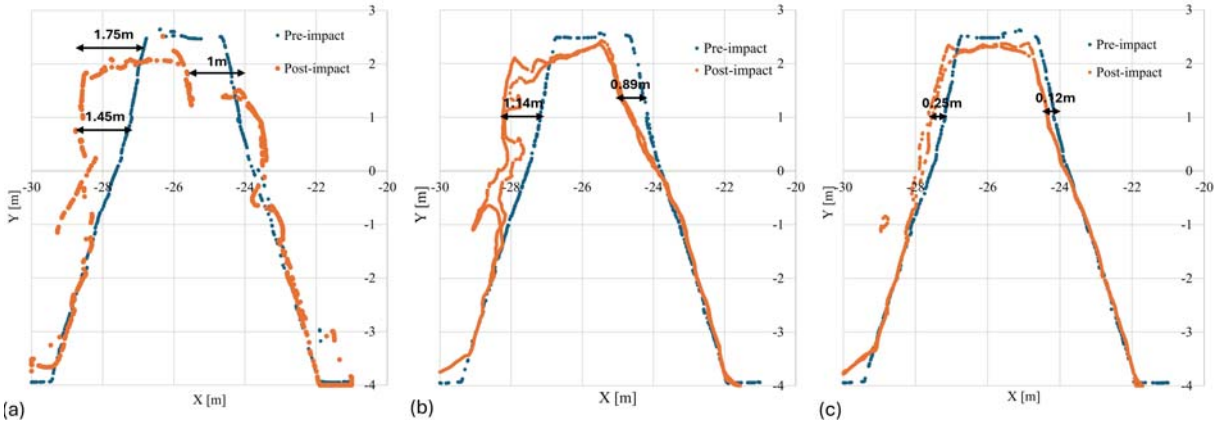


Fig. 4 Comparison of the RE-RPE cross section pre and post impact: (a) along the symmetry axis; (b) 1.5 m from the symmetry axis (in correspondence of the Green Terramesh Light module boundaries); (c) 1.75 m from the symmetry axis.

3.1 Preliminary comparison with FEM modelling

A preliminary comparison between the numerical approach proposed by Vigna (2025) and Vigna et al. (2025) for modelling the RE-RPE under impact conditions and the experimental results was carried out. Fig. 5b shows the downstream side bank predicted by the FEM model, highlighting the capability of the model to capture the large deformations experienced by the structure, as well as the final position of the block embedded within the embankment. Moreover, according to the plastic strain

distribution, the volume involved by the impact appears to be in good agreement with that observed during the experimental test.

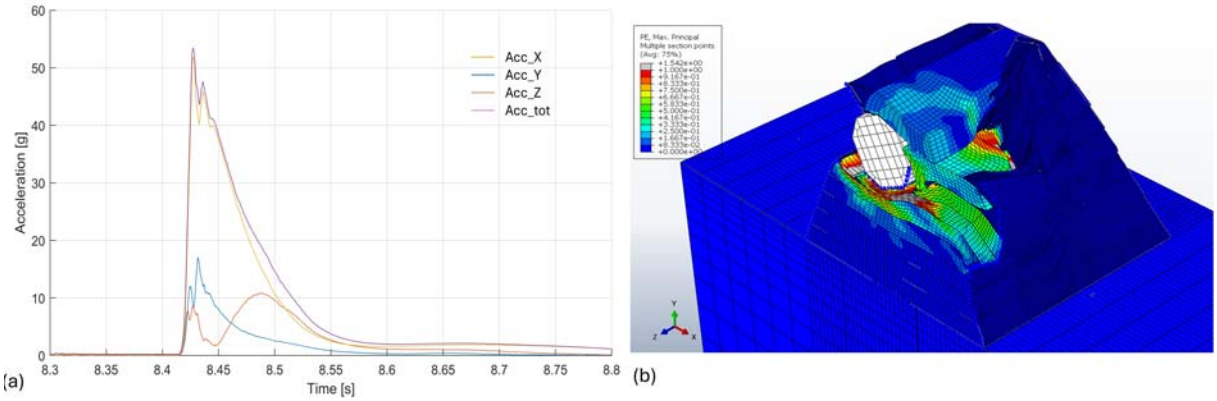


Fig. 5(a) Acceleration recorded on the block (smoothed data); (b) deformed shape obtained with the numerical modelling (PE are the plastic strain magnitude).

4 Conclusions

In this work, an innovative impact test on RE-RPEs was carried out at an impact energy of 10168 kJ, which currently represents the highest energy level investigated in experimental tests on rockfall protection works. Moreover, a key innovation of the study lies in the design and implementation of a multi-sensor monitoring system, which included a standalone device to record acceleration and angular velocity within the impacting block, together with a 32-channel data acquisition system used to record accelerations within the embankment, stresses on the foundation, and local strain fields in the reinforcements.

The monitoring system satisfactorily recorded the target physical quantities; therefore, the results presented in this paper, although only partially discussed, will form the basis for future, more in-depth analyses and interpretations of the observed phenomena. Particularly, they will be used as benchmark data for the validation of robust numerical models.

Finally, the mechanical behaviour observed during the test showed that the affected volume of the RE-RPE was limited and mainly governed by the Green Terramesh Light module length. From a maintenance perspective, this behaviour may represent an advantage for existing embankments subjected to impact events. Nevertheless, additional tests on repaired structures are required to further investigate post-impact performance.

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