Validation of numerical D.E.M. modelling of geogrid reinforced embankments for rockfall protection

DX.DOI.ORG/10.19199/2021.2-3.1121-9041.036

# *Validation of numerical D.E.M. modelling of geogrid reinforced embankments for rockfall protection*

Claudio Oggeri*,**
Chiara Ronco*
Raffaele Vinai***

* DIATI Politecnico of Torino
** IGG-CNR, Torino, Italy. claudio
*** College of Engineering, Mathematics and Physical Sciences, University of Exeter, UK

Corresponding author: Claudio Oggeri
claudio.oggeri@polito.it

*The adoption of reinforced embankments for rockfall and landslide protection purposes is an effective intervention for the reduction of risk and damages to civil facilities. These earth structures are manufactured with layers of compacted soil alternated with geosynthetics (e.g. geogrids and geotextiles) that are anchored to the outer quarterdeck frame or wrapped around it. This paper discusses the results obtained with a numerical simulation of the reinforced embankment carried out by means of a distinct element commercial (D.E.M.) code as particle code (P.F.C.). Several types of rock impacts on an embankment were simulated, varying block speeds, energies and geometrical impact conditions. Data from practical experiences of the authors and data from full-scale impact tests gathered from relevant literature, were used for the validation of the model. The main result of the work is the development of design operative suggestions that can support the selection of the design parameters of an embankment for rockfall protection purposes: its preliminary size based on impact energy level and induced damages can be outlined. The results of this provide guidance to designers and relevant stakeholders in the evaluation of risk scenarios arising from potential rock falls on infrastructures.*
***Keywords**: reinforced embankment, rockfall, risk reduction, geogrids, D.E.M. modelling.*

***Validazione di modellazione numerica D.E.M. di rilevati rinforzati con geogriglie per protezione da caduta massi.** L'impiego di rilevati rinforzati per la protezione dai fenomeni franosi e di caduta massi costituisce una efficace opzione per la riduzione del rischio e dei danni alle strutture civili. Queste opere in terra sono generalmente costituite da strati di materiale sciolto alternato con geosintetici (quali geogriglie o geotessili), i quali sono ancorati al parti di gabbie metalliche del paramento oppure risvoltate attorno ai corsi sovrapposti. Questo articolo propone i risultati ottenuti da una modellazione del rilevato sviluppata attraverso un codice commerciale agli elementi distinti (D.E.M.) di tipo particellare (P.F.C.). Diversi tipi di impatti sono stati simulati, variando la velocità dei blocchi, le energie e le condizioni geometriche di impatto. Dai dati derivanti da strutture reali esaminate direttamente dagli autori e da quelli presenti in letteratura tecnica in merito a prove di impatto in vera grandezza, si è potuto procedere a una calibrazione del modello numerico. Il principale risultato dello studio consiste nello sviluppo di indicazioni operative che possono agevolare la scelta dei parametri di progetto di un rilevato rinforzato con scopi di protezione passiva: il predimensionamento basato sui livelli energetici di impatto e i danni indotti dallo stesso sono quindi esplicitati. I risultati costituiscono un ausilio progettuale e di verifica per gli addetti alla valutazione degli scenari di rischio derivanti da eventi potenziali di caduta mi massi sulle infrastrutture.*
***Parole chiave**: rilevato rinforzato, caduta massi, riduzione del rischio, geogriglie, modellazione D.E.M.*

## *1. Introduction*

Earth reinforced embankments are extensively used in several engineering applications. The reinforcement is aimed at increasing the structural performances of compacted soil embankments in terms of strength, stiffness, and durability (Oggeri, 2011).

Different kinds of reinforcement elements are currently commercially available. In the case of reinforced embankment for rockfall protection, geogrids, geotextiles or metallic elements are adopted, usually embedded as horizontal layers within the soil structure (Figure 1). These structures are designed for absorbing repeated impacts at high energy levels (> 5000 kJ). The adoption of reinforcing elements can allow the reduction of the embankment size, which is advantageous in complex situations like mountainside locations, where usually limited space is available. When geogrid reinforced embankments are subjected to an impact, the structure receives and redistributes the load following a non-linear behaviour. Part of the kinetic energy transmitted by the impact is dissipated through the yielding and the relative sliding between geogrids and soil layers.

A fundamental parameter that drives the behaviour of the structure is the interaction between the geogrids and the soil. This interaction depends on the shear strength available at the soil/mesh interface, on the shear strength of the soil and on the additional strength supplied by the transverse elements of the geogrids.

Different approaches have been developed in order to understand the behaviour of a rockfall embankment during the impact of a rock block, mainly analytical methods, numerical models with different codes, and full scale tests. This latter represents the more reliable approach for the acceptance of the design, but due to the time and

Fig. 1 – Example of a huge earth reinforced embankment, extended parallel the mountainside, for road and houses rockfall protection. Viewpoint is downward: in the uphill wall geogrids and lateral wire mesh adopted for the construction are still visible. Additional protective works against surface runoff have been done by means of local rock fragments and wood element for environmental sustainability (credits, structural testing and approval by C.Oggeri, Northern Italy).

the costs required for setting up the test, usually only a limited set of experiments can be realistically carried out. Analytical approaches have been developed in the literature, but the complexity of the system (mechanical and physical properties of the materials, impact variables and kinetic effects) does not allow good estimations of impact forces and block penetration (Lambert *et al*. 2013).

Numerical modelling has the clear advantage of allowing the analysis of a wider range of parameters at reasonable time and costs, and can therefore provide meaningful preliminary guidance and design charts for assessing the effects of several design parameters. However, the simplifications implicitly included in the numerical modelling might lead to results that deviate from the reality, and experimental validation is required (Brinkgreve and Engin, 2013). Due to the number of parameters affecting the behaviour of the structure in the event of a rock impact, the available literature on numerical modelling validation is still disperse and fragmentary.

This paper discusses the results obtained with numerical models carried out with the Itasca PFC2D (2-dimension Particle flow code), version 3.0 (Potyondy, 2015). The embankment behaviour under impact was simulated and geogrid deformation, as well as and soil compaction, were observed and commented.

Numerical models were calibrated on full-scale test results and the outcomes were compared with results available in the literature and applied to real construction site (Figure 1). The validation exercise confirmed the reliability of the proposed design tool. The results discussed in this paper also represent a contribution to the debated issue of determining the required input parameters for reliable design and modelling of embankment for rockfall protection, as discussed by Agliardi *et al.* (2009).

## 2. Background

Many Authors have carried out researches and testing since the early 90's: full scale tests have been carried out to understand the behaviour of reinforced embankments subjected to distributed and point forces. These tests highlighted the range of variation of the kinetic energy released during typical impacts and allowed to interpret the behaviour of this type of structure in a qualitative way. After these experiences, both analytical and numerical approaches have been developed, also in the stream of Eurocodes requirements.

### 2.1. Relevant references

Burroughs *et al.* (1993) studied the behaviour of a geosynthetic reinforced embankment with vertical walls. Blocks of different weight (190 ÷ 8170 kg) and pseudo cubical size were dropped against the embankment. After rolling, the impact energy values were ranging between 8 and 1500 kJ with a velocity of about 5.5 ÷ 19.2 m/s. The recorded penetration and extrusions on the embankment were about 90 cm and 70 cm on the two opposite embankment faces respectively.

Hearn *et al.* (1995) tested three rockfall embankment prototypes made of compacted granular soil, using non-woven geotextile bags wrapped around the walls (which were covered with wood panels). Tests allowed the assessment of the amount of kinetic energy released by the impact that led to the collapse of the structure, and therefore of the critical size of impacting blocks. Yoshida (1999) and Nomura *et al.* (2002) studied the effect of the impact of different blocks against an embankment, whose core was made of horizontal layers reinforced with geosynthetic materials, whilst the impact side was made of two layers of sand bags. The tests were aimed to verify the behaviour of soft and deformable soil. The penetration values were 2.6 ÷ 30 cm, under an impact energy ranging from 60 to 2700 kJ.

Plassiard *et al.* (2008) assessed the shear strength on the soil/reinforcement interface by means of a distinct element simulation of independent soil layers and embedded reinforcing elements. Plassiard and Donzé (2010) studied the shape of the embankment in order to optimise the structure design. Their main conclusion was that the geometry is the key factor in establishing the dissipative capacity, whereas the filling material properties are less relevant. Lambert *et al.* (2009) investigated the role of a surface reinforcement with filled geocells in order to homogenise the overall stress distribution after impact. Lambert and Bourrier (2013) proposed a comprehensive review of current embankment design, in which achievements and limitations for a proper design were pointed out. The impact of a boulder, whose typical velocity ranges from 5 to 30 m/s and for which the mass is limited to tens of thousands of kilograms, results in a dynamic localised stress whose duration is generally less than 0.2 s, thus generating a strain velocity rate in the direction of the impact. Various mechanisms are involved during the impact: compressive wave propagation in a finite volume, soil compaction, friction and crushing of granular particles leading to plastic deformation and large displacements of the embankment, etc. The related effects vary drastically in space and time while depending on the embankment size and geometry as well as on the properties of adopted materials. For these reasons, the analytical models that have been developed to date fail to give good representation of the impact effects on the embankment (Lambert *et al.* 2013).

Cellular rockfall protection embankments were also proposed, with the advantage of adapting the properties of the filling material to the cell position in the structure. Different types of filling materials were tested with the aim of optimizing the behaviour of structure under the impact. Numerical modelling was also carried out to simulate the behaviour of the structure at different scales, from material to full structure (Lambert *et al.* 2014).

Recent contributions have been given on modelling the effects of geosynthetic contacts with reinforcing mesh (Bertrand *et al.*, 2008), investigating the interaction between geogrid and ballast using the discrete element method (Fellerec *et al.*, 2012), and on experimental and numerical methods for the study of soil–geosynthetic interaction (Palmeira, 2009). The load transfer behaviour between geogrid elements and sand was tested and modelled with PFC code providing a detail of the mechanism at a microscopic scale (Wang *et al.*, 2014). The modelling of geocells using 3D finite difference software was used to investigate the load distribution and the interface behaviour of the reinforcement (Hegde *et al.*, 2015). Bourrier *et al.* (2011) investigated a multiscale approach, for studying the dynamic impact on embankment. Vieira *et al.* (2013) characterised the soil-geotextile interface through direct shear tests. Results from physical model studies carried out on reinforced soil walls compacted in different ways are reported in Ehrlich *et al.* (2012), whilst large-scale plane-strain compression tests were carried out on loose and dense sand using four types of geogrids as described in Liua *et al.* (2014). Eventually, Villard *et al.* (2009) and by Li *et al.* (2015) investigated earth reinforced structures under dynamic loading by comparing results from different numerical approaches and physical testing.

Cuomo *et al.* (2019) modelled barriers conceived as a multilayered embankment, reinforced by geogrids wrapped around the facing. In this work both static and dynamic stress–strain analyses have been performed through a FEM code (Plaxis v. 8.5) to simulate the deformation mechanisms and the ultimate limit states. Within the obtained results, the displacement of the reinforced layers along the geogrids with an acceptable performance of the whole barrier have been emphasized.

Relevant evidences from full scale tests were reported in the works carried out by the Politecnico of Torino research group at the Meano test site about two decades ago (extensively cited and in origin developed with reinforcing systems described in Peila *et al.* 2002, Oggeri *et al.* 2004, Peila *et al.* 2007, Ronco *et al.* 2009 and Ronco *et al.* 2010), where a cableway able to drop blocks with a ballistic trajectory was set up. Four series of tests were carried out, varying the embankment reinforcement features, the mechanical characteristics of the fill, and the impact energy.

Lambert and Kister (2018) published a useful summary of the relationship between the block kinetic energy and the displacement of the downhill side of the embankment, obtained by collecting available data from real size tests.

### *2.2. Interpretation of literature data*

While results can be found in the published cited works, a brief summary of test setup and outcomes is presented hereafter, having the results from those tests been used for the validation of the numerical simulation presented in this paper.

Worked case. Step 1): The embankment had the following geometrical features: height 4.2 m; base width 5 m, side inclination referring to the horizontal 67°. The reinforcement was made of high-density polyethylene extruded geogrids with unit weight 350 g/m$^2$ and tensile strength 50 kN/m. The backfilling was made of coarse and well graded soil, mainly composed of gravel and sand with a silt fraction, with friction angle $\phi$ = 34° ÷ 36°, cohesion c = 8 ÷ 12 kPa and unit weight $\gamma$ = 19.0 ÷ 20.5 kN/m$^3$.

Step 2): The impact tests were carried out by dropping a concrete block with a certain initial speed against the embankment. Different blocks were used, thus obtaining different levels of kinetic energy from impact. Typical block mass was in the order of 3000 ÷ 5000 kg and impact speed was in the range of 28 ÷ 30 m/s.

In order to observe the progressive damage of the structure, multiple impacts were also performed. Typically, the structure was able to absorb at least 2-3 impacts before collapsing or becoming unsuitable for standing further impacts. The block impacting the upper part, where the embankment had a thickness of about 1.2 m, created a footprint with a maximum depth of 0.6 m (measured at right angles to the face), while the extrusion on the opposite downstream side was of about 0.17 m. No relevant geometric changes in the shape were observed outside the area directly affected by the impact, whilst a tension crack was formed in the backfilling soil along the layer affected directly by the impact, with a maximum opening of 140 mm. A plastic deformation of the geogrid was also observed. Cracks or yielding strain are common in reinforced embankments for different geosynthetics (Figure 2).

Step 3): A series of tests was carried out where the geometry of the embankment was kept constant and the impact kinetic energy was gradually increased, in order to assess the ultimate strength condition of the structure.The embankment showed a failure of the reinforcements and extended yielding of the fill after two consecutive impacts characterised by a kinetic energy of at least 4200 kJ.

Fig. 2 – Typical tension cracks formed inside the disassembled body of the embankment: on the left woven geogrids elongated in collapsed earth support structure; on the right extruded geogrid elongated after the impact of the block in a protection embankment. Same graphical scale. (credits personal archive C.Oggeri).

Step 4): In order to assess the contribution of the reinforcement, an unreinforced embankment, i.e. made of compacted soil only, was built with the same geometry and maintaining the kinetic energy equal to 4200 kJ, as for the previous test. The embankment collapsed after the first impact, even though the block was still stopped.

## 3. Preliminary F.E.M. and new D.E.M. numerical models

DEM and FEM represent two different modes for discretization, both valid. Advantage of FEM is the comprehensive definition of material properties, for DEM the possibility to better follow kinematics. Disadvantages in FEM is the lack of stability for large displacements, for DEM the computational limits in particle size reduction.

### 3.1 Preliminary F.E.M. modelling

An extensive and original numerical modelling of reinforced embankment was developed by Ronco (2010, unpublished) as a design tool. The model was developed with Abaqus/Explicit code (which is a F.E.M. model) in the dynamic field, running stress-strain analyses related to dynamic changes in parameters. Obtained results were verified against the Eurocode prescriptions for the optimisation of the design parameters. The simulation allowed to assess the relationship between the impact energy and the block penetration/extrusion when the geometrical features of the embankment and the impact point were varied. Results from the numerical simulation with Abaqus code were used as a base for the validation of the numerical simulation method proposed in this paper.

The F.E.M. numerical approach was developed in three phases:

1) The back-analysis of dynamic compaction tests performed on compacted soils, for the assessment of the mechanical and physical input parameters.
2) The study of the behaviour of the reinforced and unreinforced embankments under the impact of blocks.
3) The analysis of the behaviour of the reinforcing elements during impact within the embankment.

The embankments layers were modelled as independent elements, according to the actual construction procedure. The boundary conditions for the model were represented by a rigid bond for the base layer. The Drucker-Prager yield criterion was adopted and appropriate strength parameters were assessed after the preliminary phases. The impacting block was simulated as a rigid element with a regular shape (Figure 3, left and right). Drucker-Prager is a good choice as it if fitting pressure acting problems and it is well implemented in the code settings.

Lateral diffusion in a consequence of the impact and it develops also in static. Construction features drive the shape and the extension of this parameter, and also the local kinematic and reaction: homogeneous filling, strata separation, type of interface (contact or interlocking), scale effect between stratum and block, compaction level of filling (dilatant or contracting behavior) are all factors that can modify the expected results.

The modelled results compared well to the penetration/extrusion values along the two embankment sides, which were measured during full-scale tests. The modelling was then developed considering four types of embankments with different geometries. The impact kinetic energy was also increased until collapse of the embankments, represented by the condition of a deformed shape of the layers which are no longer self-supporting.

Results in terms of block penetration and extrusion distances for the two opposite walls of the embankments, taking into account parameters such as the impact energy and the ratio of the embankment thickness and elevation in correspondence to the impact point (sp/h), are shown in Figure 4 left. When the ratio sp/h ratio was increased, a reduction of the critical impact energy was observed for the ultimate state of the embankment, see Figure 4 right (Oggeri, 2011).

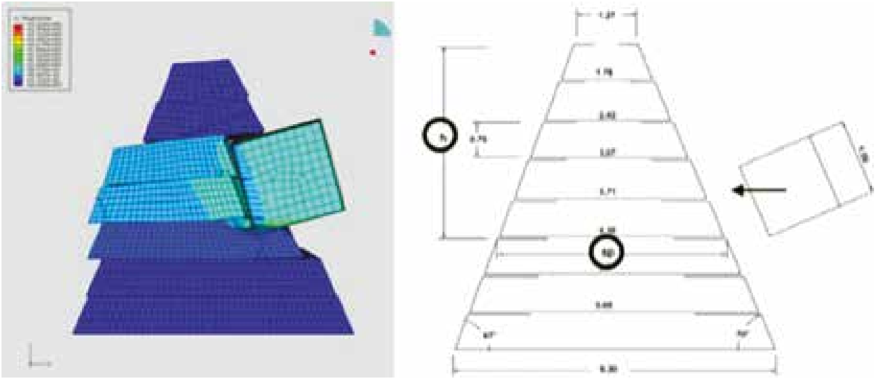

Fig. 3 – Left: Embankment model with the Abaqus/Explicit code (Ronco, 2010, unpublished). Right: Embankment scheme, with the indication of "*h*" and "*sp*" geometric parameters and ideal position of block at impact.

### *3.2 New D.E.M. modelling and calibration*

In order to understand the behaviour under impact, and the displacement measured uphill and downhill, it is useful to have a precise scheme of the design and of the materials adopted during the construction. A sector of embankment has been built for experimental site validation of operative behaviour, following requirements and testing operated by the Authors. New modelling has been done by means of internal computational resources (code) provided by C.Oggeri academic funds, and compared with the behavior of an embankment on a real construction site followed by C.Oggeri for professional expertise (Figure 1).

Controls on the soil parameters during construction, on the geosynthetic installation and on the obtained compaction are of great influence because these aspects are essential in order to avoid excessive scattering of expected adsorbed energy at impact: e.g., stiffness of each soil stratum is measured by means of a plate loading test.

Itasca PFC2D is a distinct element method, where the elements are modelled as spherical particles

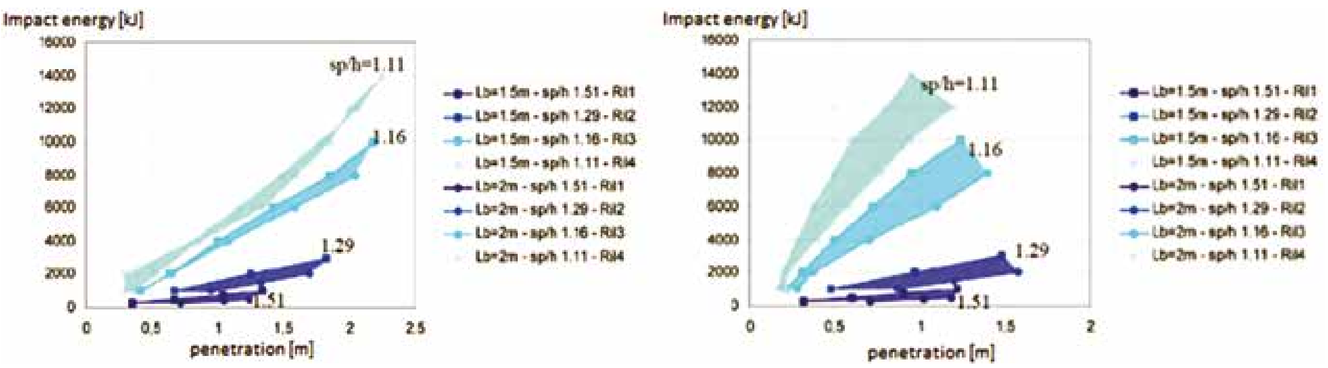


Fig. 4 – Penetration on the uphill wall (left) and bulging on the downhill wall (right) for different values of the impact energy and sp/h ratio. Results were obtained from the F.E.M. numerical modelling of impacts with 1.5 and 2 m wide cubic blocks.

able to move and interact according to their physical and mechanical properties, interface properties and acting force field. These spheres can represent the granular nature of the ground and can simulate the deformation of soil as a result of a stress variation. Each element is described by its intrinsic properties (stiffness, density, radius, velocity and friction) and by contact properties.

The modelled embankment is composed of seven layers. Each layer is built inside a formwork that contains the granular backfilling compacted during the embankment construction. A layer of geosynthetic is then added and anchored at both ends. Each layer interacts with the neighbour elements. Layers can absorb the kinetic energy of the impacting block through two main mechanisms: (a) the soil compaction beneath and around the block impact area, and (b) the sliding of a layer in respect with the neighbour layers.

The main components of the embankment are represented by the external formwork (usually a stiff steel wire mesh), the granular soil, the reinforcement element (a geogrid in this case), which is represented as a chain of connected elements, and the block, which is simulated with solid spheres with high connection strength.

The code elaborates the initial condition, during which gravity (or other field stress state) and material properties are applied. Appropriate initial conditions can be determined by applying external forces, removing boundaries or elements in certain regions, or changing some of the physical and mechanical properties of the elements. The aim of this simulation was to study the effects of an impact originating from a block hitting the reinforced embankment. An initial speed was applied to the block with a defined mass in order to obtain the desired impact energy. The code ran on a cyclic basis, by recalculating the position and forces of the elements at each iteration, until a convergence state was reached. The main output was the stress state and the arrangement of the elements, including the failure of the overloaded ones, at the end of each cycle. Among physical and mechanical properties to be determined, a particular attention was required for the contact properties, i.e. "contact bond" properties. These are defined in the code by the normal strength *n_bond* (which is equivalent to the real tensile strength between the particles) and the shear strength *s_bond* (which is equivalent to the dilatancy that develops between two sliding particles). Contact conditions control the slipping mechanisms between the spheres (preventing or modulating them). The deformation of the model is calculated according to the parameters assigned to the interfaces where the spheres physically interact, as each singular sphere is infinitely stiff (i.e. it cannot deform).

The main model parameters of the constituents are listed in Table 1.

The soil used as filling material was modelled as cohesionless and it is characterised by a friction angle of 35°. In order to take into account the presence of fine soil particles, a suitable contact bond was adopted among the soil particles for achieving convergence of a high number of elements within an acceptable time. The compaction of the soil was simulated through a sequence of drops under gravity stress field, until the desired porosity (n = 12÷16 %) was obtained.

The geogrid was simulated with an alignment of spheres, whose initial position was defined by a code function. In order to account for the flexibility of the geogrid and the roughness of the soil underneath, the bond between the spheres was defined with parallel bond contact only. The friction coefficient for the soil – geogrid interface was assumed equal to 0.46, according to previous work (Ronco *et al.*, 2009). Calibration of geogrid was done simply by simulating a pull out test by using stress strain curve of the geogrid and applying an external force. A further reduction factor of 0.65 applied to the friction coefficient was included for the full scale model. Reduction factor is linked to the physical interface working mode: each geotextile has its own way to interact with different soils and compaction. Palmeira (2009) and Wang *et al.* (2014) have widely studied this key factor and it is reported on available textbooks. Value of 0.65 is reasonable for the worked model. Eventually, the upper end of all the formworks was anchored to the relevant geogrid, in order to avoid an immediate pull-out failure during the impact. The anchoring was simulated by a contact bond between the adjacent spheres of formwork and geogrid

Tab. 1 – Main parameters used in the model.

| Component | Unit weight [kg/m$^3$] | Sphere diameter [m] | Normal stiffness [N/m] | Shear stiffness [N/m] | Normal parallel/contact bond [N/m] | Shear parallel/contact bond [N/m] |
|---|---|---|---|---|---|---|
| Soil | 2000 | 0.02;0.04 | $0.8\times10^5$ | $0.8\times10^5$ | - | - |
| Wire mesh | 3000 | 0.04 | $0.3\times10^6$ | $0.3\times10^6$ | $45\times10^3$ | $36\times10^3$ |
| Geogrid | 1000 | 0.04 | $0.3\times10^6$ | $0.3\times10^6$ | $50\times10^3$ | $7.5\times10^3$ |

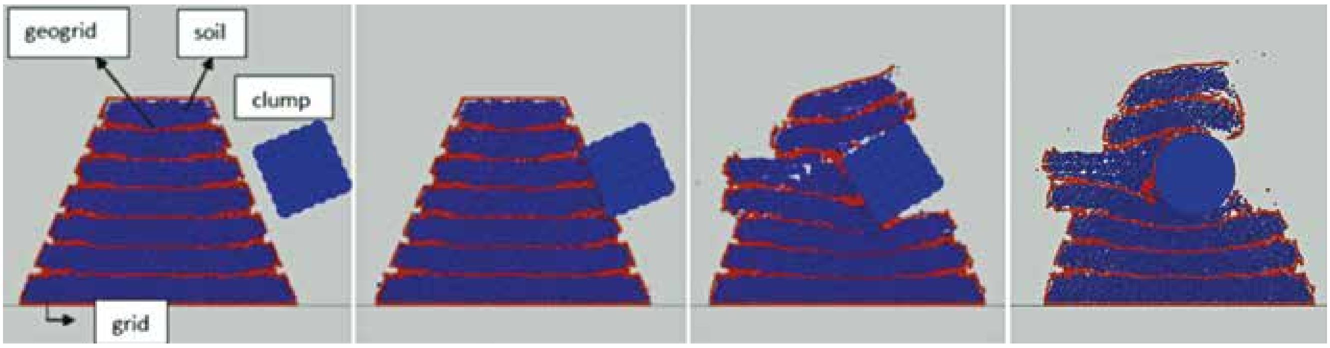


Fig. 5 – Impact modelling with PFC2D, for cubic (left) and spherical (right) blocks. Foot prints from models are embedding the block shape.

respectively, assigning the same strength properties as the geogrid.

The impacting block was simulated with a "clump", i.e. a rigid body with deformable boundaries, with a velocity vector applied to the centre of the block mass (Figure 5).

The impact of a 1.17 m wide cubic block, with a mass of 5000 kg was simulated. The block landed on the fifth and sixth layers of the embankment with a velocity of about 31 m/s. When assuming an overall stiffness of $0.3x10^3$ N/m, the penetration of the block into the upstream wall (measured orthogonally to the face) was 0.7 m, while the maximum bulging off the downstream wall was 0.17 m. The results obtained by the model matched those measured in the cited full scale tests with a satisfactory precision (Ronco *et al.*, 2010).

### 3.3. Parametric analysis with the calibrated model

After the calibration analysis, further impact conditions were modelled. Thanks to the fine dimension of discrete elements simulated with the model, it was possible to observe the behaviour of the reinforcing elements and soil fill, even in the case of the formation of tension cracks. A close agreement with the results obtained with the previous numerical modelling carried out with Abaqus code was observed. Table 2 summarises the obtained results. For all cases, energy at impact has been verified with fine scanning of video frames for velocity detection. The scope of the various model types is to recognise separately the effects of each main input parameter (mass, velocity, shape) on the final behaviour of the embankment under impact, in terms of wall displacements. Parametric modelling has examined eight different conditions: effects of block velocity, effects of increased block velocity, effect of increased block mass, effect of increased velocity and block mass, effect of increased velocity, effect on unreinforced soil, effect of the change of block shape to a sphere, effect of the different discretisation of modelled soil.

## 4. Discussion

The non-homogeneous behaviour of the embankment can be attributed to its layered structure and to the stress distribution after the impact, which is concentrated on a limited surface of the structure.

The kinetic energy is dissipated within the layers by the mechanisms of reciprocal layer sliding and of soil rearrangement, this latter inducing soil plasticisation and compaction. Spherical failure surfaces are often observed under the block on unreinforced embankment, while geogrid levels in a reinforced embankment can control the deformation process.

The relationship between the impact kinetic energy and the calculated displacement is shown in Figure 6. When the impact is applied in the same point on the embankment, a linear trend of the displacements vs. energy data points can be observed.

It was observed that, keeping the impact energy constant, an increased weight of the block resulted in higher damage of the embankment. This outcome should be considered in the general evaluation of performance capabilities

Tab. 2 – Impact conditions and deformation outputs from D.E.M. modelling.

| Block shape | Mass [kg] | Impact kinetic energy [kJ] | Impact velocity [m/s] | Uphill penetration [m] | Downhill sliding [m] |
|---|---|---|---|---|---|
| cubic | 8700 | 1000 | 15.2 | 0.42 | 0.22 |
| cubic | 8700 | 4000 | 30.3 | 1.00 | 0.50 |
| cubic | 20000 | 1000 | 10.0 | 0.80 | 0.40 |
| cubic | 20000 | 3000 | 20.0 | 1.15 | 0.90 |
| cubic | 20000 | 9000 | 30.0 | 2.40 | 1.80 |
| spherical | 8700 | 8000 | 42.9 | 2.40 | 1.00 |

of embankments when evaluating the "reference block" in the design stage. However, this behaviour is less important for larger widths of the embankment, due to the inertia of the structure.

The increase in impact energy resulted in upstream penetration values slightly higher than the corresponding downstream sliding movements, due to the compaction of the soil beneath the block developing on the impact side and not on the opposite wall.

When comparing the block shapes (spherical or cubic), it can be observed that: a) layer sliding on the downstream wall was not influenced by the shape of the block; b) the same kinetic energy and impact velocity led to a deeper footprint of the block in case of spherical shape impact; c) the embankment reached the limit state condition for lower impact energy, since a sphere impact involves a greater volume of soil in the collision. This outcome was already observed by the Abaqus model simulation (Ronco, 2010, unpublished).

As far as the adoption of different sphere diameters for modelling the soil is concerned, it was observed that, with the applied refinement, the specific surface area of the spheres was increased. Consequently, it was necessary to reduce the corresponding "fictitious" cohesion of the soil in order to obtain similar deformation values, as the structure response was stiffer in the refined model. This result is in agreement with the expected effect of a well graded grain size distribution of the soil (i.e. porosity reduction and compaction increase).

Geogrid deformation was evaluated at the interfaces between sliding layers as a rupture of the anchoring points. As the model spherical elements cannot deform, the strain is simulated as an increase in the space between the elements. In this way, it is possible to consider the stress/strain relationship of the geogrid, which is fundamental for appreciating the performance of the structure. Spheres modelling the geogrid, even though no longer physically in contact, were able to maintain their alignment and connections until the failure of the structure. This condition is represented in the model by the creation of separate alignments. If several contacts fail, a random dispersion of spheres occurs.

## 5. Conclusions

A numerical model of geogrid reinforced structures for rockfall protection was set up after a consistent back analysis of both full scale tests and new on site evidences on worked structures. After an initial F.E.M. modelling approach carried out by the Authors, a new code has been adopted to compare and assess the available results and in order to apply it at a new construction site. Both modelling activities allowed for the prediction of the performances of different embankment geometries, under different impact conditions and with the adoption of different reinforcements.

The D.E.M. modelling approach described in this paper is based on the application of Itasca PFC2D. The obtained results compared well with the old F.E.M. modelling with Abaqus.

The output of the code consists of graphical diagrams in which displacements and damage (failures, tension cracks) can be highlighted. As these are among the most important concerns of rockfall protection devices, the PFC2D modelling can be considered satisfactory. Since the embankment is a linear structure, the two-dimensional approach is relevant. The effects of different block mass, kinetic energy, and block geometry were assessed on a model of reinforced embankment. A model simulating the impact on unreinforced embankment was also developed for comparison purposes.

The main outcomes from this research were the following.

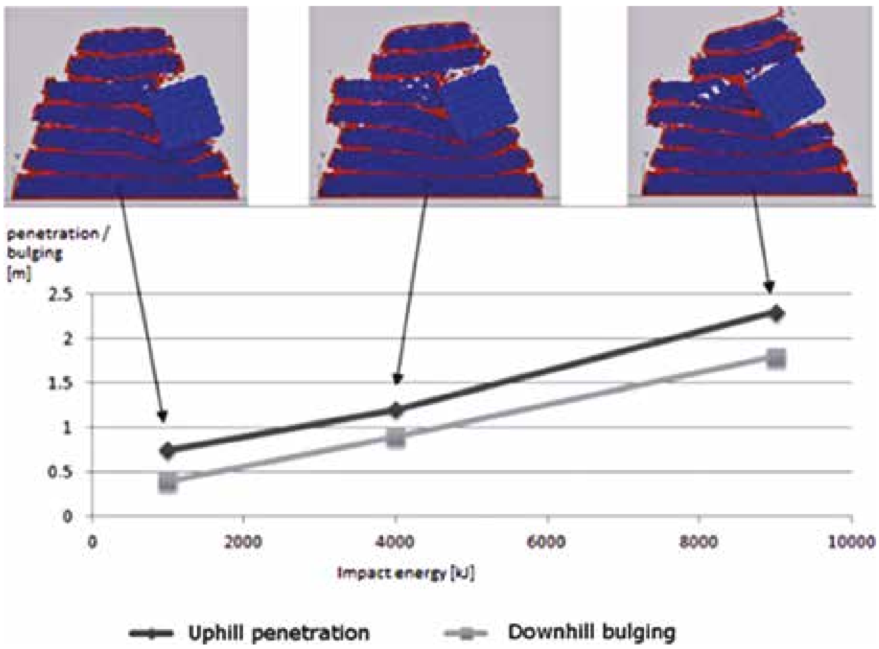


Fig. 6 – Calculated D.E.M. wall displacement of the reinforced embankment.

a) The relationship between the impact kinetic energy and the calculated displacement followed a linear trend.
b) The mass of the block had an influence on the displacement development: a bigger block showed a higher deformation on the embankment than a smaller block with the same kinetic energy.
c) The shape of the block had an influence on the displacement development as well. Spherical blocks caused higher deformation in the embankment than cubic blocks with the same kinetic energy.
d) 2D model is exhibiting a challenging displacement because it is focusing on planar strain, as geometrical model of the embankment is claiming for.
e) The size and the number of the model elements, i.e. the "ball" dimension, had an effect on the stiffness of the structure. Higher fineness of elements (i.e. smaller and more graded soil particles) led to reduced deformation when the fictitious cohesion was kept the same utilised for coarser model. This effect reflects the different porosity and compaction level that can be reached with better graded grain distribution.

Possible adaptation of the model includes a more accurate soil simulation by using small spheres characterised by different diameters, while the adoption of a three dimensional code would be useful for the understanding of the local behaviour of the geogrids, which work as a 3D reinforcing structure, and for assessing the geogrid – soil interaction more accurately, through an analysis of the interlocking phenomenon of the soil grains inside the mesh. The last step, at a practical design level, consists of the analytical verification of structural details and geometrical compatibility.

## References

Agliardi, F., Crosta, G.B., Frattini, P., 2009. *Integrating rockfall risk assessment and countermeasure design by 3D modelling techniques*. Natural Hazards and Earth System Sciences, 9(4), 1059.

Bertrand, D., Nicot, F., Gotteland, P., Lambert, S., 2008. *Discrete element method (DEM) numerical modeling of double-twisted hexagonal mesh*. Canadian Geotechnical Journal.

Bourrier, F., Lambert, S., Heymann, A., Gotteland, P., Nicot, F., 2011. *How multi-scale approaches can benefit cellular structure design*. Canadian Geotechnical Journal.

Brinkgreve, R.B.J., Engin, E., 2013. *Validation of geotechnical finite element analysis*. Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris.

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

Cuomo, S., Moretti, S., Frigo, L., Aversa, S., 2020. *Deformation mechanisms of deformable geosynthetics-reinforced barriers (DGRB) impacted by debris avalanches.* Bulletin of Engineering Geology and the Environment.

Ehrlich, M., Mirmoradia, S.H., Saramago, R.P., 2012. *Evaluation of the effect of compaction on the behaviour of geosynthetic – reinforced soil walls*. Geotextiles and Geomembranes, vol. 34, Oct. 2012, pp. 108-115.

Ferellec, J.-F., McDowell, G.R., 2012. *Modelling of ballast–geogrid interaction using the discrete-element method*. Geosynthetics International, Vol.19 Issue 6, Dec. 2012, pp. 470-479.

Hearn, G., Barrett, R.K., Henson, H.H., 1995. *Testing and modelling of two rockfall barriers*, Transportation research record n° 1504, National Research Council, Washington DC, 1995.

Hegde, A., Sitharam, T.G., 2015. *3-Dimensional numerical modelling of geocell reinforced sand beds.* Geotextiles and Geomembranes, Volume 43, Issue 2, April 2015, pag. 171-181.

Heymann, A., 2012. *Approche expérimentale du comportement mécanique des géo-ouvrages à technologie cellulaire. Application aux ouvrages pare-blocs*. (Doctoral dissertation). University Joseph Fourier, Grenoble (in French).

Lambert, S., Gotteland, P., Nicot, F., 2009. *Experimental study of the impact response of geocells as components of rockfall protection embankments*. Natural Hazards and Earth System Sciences, 9, 459-467.

Lambert, S., Bourrier, F., 2013. *Design of rockfall protection embankments: a review*. Engineering Geology 154, 77-88.

Lambert, S., Heymann, A., Gotteland, P., Nicot, F., 2014. *Real-scale investigation of the kinematic response of a rockfall protection embankment*. Natural Hazards Earth Systems Sciences.

Lambert, S., Kister, B., 2018. *Efficiency assessment of existing rockfall protection embankments based on an impact strength criterion*. Engineering Geology 243, 2018, 1-9.

Li, M., Yu, H., Wang, J., Xia, X., Chen, J., 2015. *A multiscale coupling approach between discrete element method and finite difference method for dynamic analysis*. International Journal Numerical Method in Engineering. 102:1-21.

Liua, C.N., Yang, K.H., Nguyenc, M.D., 2014. *Behaviour of geogrid–reinforced sand and effect of reinforcement anchorage in large-scale plane strain compression*. Geotextiles and Geomembranes, Vol. 42, Issue 5, October 2014, pp. 479-493.

Maegawa, K., Tajima, T., Yokota T.and Tohda, M., 2011. *Slope-rockfall tests on wall embankments reinforced with geosynthetics.* In Proceedings of the 6th International Structural Engineering and Construction Conference, Zürich, Switzerland (pp. 641-646).

Nomura, T., Inoue, S., Fuchigami, M., Yokota, Y., Kubo, T., Tatta, N., Arai, K., 2002. *Experimental research of reinforced soil wall for rock-fall protection*. Proceedings 7th International conference on geosynthetics, 303-308.

Oggeri, C., Peila, D., Recalcati, P., 2004. *Rilevati paramassi*. In Proceedings Convegno Bonifica di versanti rocciosi per la protezione del territorio, GEAM, pp. 191-232 (In Italian).

Oggeri, C., 2011. *Impact features on reinforced embankments used for rockfall protection on the base of Eurocodes and national technical law*. Proceedings. Rocexs2011, Interdisciplinary Rockfall Workshop 18 May 2011, Innsbruck-Igls.

Palmeira, E.M., 2009. *Soil – geosynthetic interaction: Modelling and analysis*. Geotextiles and Geomembranes, vol. 27, Issue 5, Oct. 2009, p. 368-390.

Peila, D., Oggeri, C., Castiglia, C., Recalcati, P., Rimoldi, P., 2002. *Testing and modelling geogrid reinforced soil embankment to high energy rock impact*. Proceedings of 7th I.C.G.International Conference on Geosynthetics, Nice, 133-136.

Peila, D., Oggeri, C., Castiglia, C., 2007. *Ground reinforced embankments for rockfall protection: design and evaluation of full scale tests*. Landslides, Springer Verlag, Vol. 4, ISSN: 1612-510X.

Plassiard, J.P., Donzé, F.V., Lorentz, J., 2008. *Simulations of rockfall impacts on embankments using a discrete element method*. Proceedings of Interdisciplinary Workshop on Rockfall Protection, 84-86.

Plassiard, J.P., Donzé, F.V., 2010. *Optimizing the design of rockfall embankments with a discrete element method*. Engineering Structures, 3817-3826.

Potyondy, D.O. 2015. *The Bonded-Particle Model as a Tool for Rock Mechanics Research and Application: Current Trends and Future Directions*. Geosystem Engineering, 18 (1), 1-28.

Ronco, C., 2010. *I rilevati in terra rinforzata utilizzati per la protezione dei versanti: verifiche numeriche e analitiche di supporto alla progettazione*. Doctoral dissertation, DIATI Politecnico of Torino (in Italian).

Ronco, C., Oggeri, C., Peila, D., 2009. *Design of reinforced ground embankment used for rockfall protection.* Natural Hazards Earth Systems Sciences, 9, 1189-1199.

Ronco, C., Oggeri, C., Peila, D., Bertolo, P., Ferraiolo, F., Giacchetti, G., 2010. *Numerical modeling of ground reinforced embankments used for rockfall protection*. In Advances in Geomaterials and Structures, 3rd Euro-Mediterranean Symposium on Advances in Geomaterials and Structures, Djerba, 269-276.

Vieira, C.S., Lopes, M.L., Caldeira, L.M., 2013. *Sand-geotextile interface characterisation through monotonic and cyclic direct shear tests*. Geosynthetics International, Vol. 20 Issue 1, Feb. 2013, pp. 26-38.

Villard, P., Chevalier, B., Le Hello, B., Combe, G., 2009. *Coupling between finite and discrete element methods for the modelling of earth structures reinforced by geosynthetic*. Computer Geotechnics. DOI:10.1016/j.compgeo.2008.11.005.

Yoshida, H., 1999. *Recent experimental studies on rockfall control in Japan*. Proceedings. Joint Japan-Swiss Scientific Seminar on Impact load by rock fall and design of protection structures, 69-78.

Wang, Z., Jacobs, F., Ziegler, M., 2014. *Visualization of load transfer behaviour between geogrid and sand using PFC2D*. Geotextiles and Geomembranes, vol. 42, Issue 2, Apr. 2014, pp. 83-90.