ISGSR 2011 - Vogt, Schuppener, Straub & Bräu (eds) - © 2011 Bundesanstalt für Wasserbau ISBN 978-3-939230-01-4

The effectiveness of protection systems toward rockfall risk mitigation

G. Gottardi, L. Govoni, A. Mentani & M. Ranalli
Bologna University

C. Strada
Autonomous Province of Bolzano

ABSTRACT: A comprehensive method for rockfall risk analysis has been recently proposed by the Autonomous Province of Bolzano within the context of European project PARAmount (imProved Accessibility, Reliability and safety of Alpine transport infrastructure related to MOUNTainous hazard in a changing climate). The procedure is especially aimed to a proper planning of effective countermeasures through a rational management of the existent. To such purpose, the process of hazard evaluation has been especially designed to accommodate the presence of protection systems located in the area interested by the analysis. The application of the procedure requires a thorough knowledge of the considered works, which includes passive and active protection systems. With reference to the passive measures, the paper presents a numerical study of falling rock protection barriers at present installed within the Province territory. The investigation addresses the actual effectiveness of these structures toward hazard mitigation. Preliminary analyses and results, concerning a carefully carried out selection of barrier types occurring on the territory are described and commented.

Keywords: hazard, falling rock protection barriers, numerical modelling

1 INTRODUCTION

Rockfall consists of the free falling, bouncing, rolling and sliding of blocks of different sizes detached from a rock slope (Giani, 1992). Typical of mountainous areas the phenomenon is one of the most frequent geological hazard. The related risk can be particularly high in areas extensively crossed by roads and railway arteries and characterized by densely populated towns and tourist infrastructures, such as for instance, the Alpine space. Owing to the ever increasing urban expansion as well as climate changes, the interference between human activities and natural events has considerably grown in these areas. Due to these circumstances, the development of appropriate tools for landslide risk analysis and management has become a crucial issue for the local administrations and agencies in charge of protecting the territory (Fell and Hartford, 1997; Lee and Jones, 2004).

An effective planning of rockfall countermeasures needs to rely on a rational management of the existent. An adequate risk analysis should allow to take in due consideration the presence of the protection systems on the concerned area, either within the rockfall hazard (H) or vulnerability (V) evaluation. A few risk assessment procedures which address the presence of protection structures on the territory are currently available (Oggeri and Tosco 2005, Corominas et al. 2005).

Within the context of the European project PARAmount (imProved Accessibility, Reliability and safety of Alpine transport infrastructure related to MOUNTainous hazard in a changing climate), the Autonomous Province of Bolzano (Italy) has recently developed a tool for rockfall risk analysis. In the procedure, the process of hazard assessment is especially devised to accommodate the presence of existing passive and active countermeasures, yet carefully registered in a complete and constantly updated Province's inventory of protection works.

Among ditches, sheds, earth retaining structures, wire nets, the inventory includes data on falling rock protection barriers, metallic structures designed to intercept and stop the blocks moving along a slope in a rockfall event. Easy to be installed and maintained, these structures are able to stop blocks having a wide range of kinetic energy values, from only a few up to more than 4500 kJ. For these reasons, over the last three decades, they have been used extensively, especially when urgent conditions required fast solutions and neither a comprehensive planning nor proper design could be completed.

As a result, the behaviour of a significant portion of formerly devised and installed protection barriers is currently uncertain. These circumstances make extremely problematic to complete the procedure of hazard evaluation which at least requires the structure nominal capacity in term of kinetic energy to be known (Figure 1).

This lack of information can be reasonably covered by a suitably designed numerical study addressing the behaviour of these structures in dynamic condition. A numerical investigation as such should be based on detailed information on the geometries, properties and preservation state of the concerned work.

The paper presents preliminary results of an extensive study of the falling rock protection barriers installed within the Autonomous Province of Bolzano and registered in the Province's inventory of the protection works. In particular, a numerical study of selected types of barriers, chosen among the most frequently occurring is presented. The study enables to attain results on the nominal response of a significant portion of falling rock protection barriers of the territory. These data provide the starting point for the investigation of the actual barrier response which also account for the specific on-site arrangement, positioning and state of maintenance.

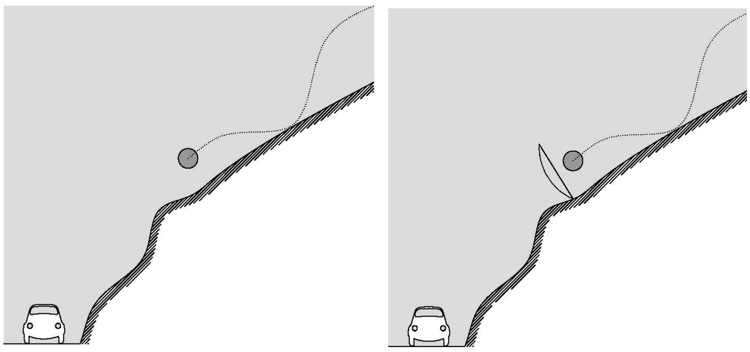

Figure 1. The role of falling rock protection barriers in the process of hazard assessment.

2 HAZARD ASSESSMENT WHITHIN THE AUTONOMOUS PROVINCE OF BOLZANO

Within the Autonomous Province of Bolzano a tool for rockfall risk analysis has been recently developed. In the procedure, the natural slope hazard (H) is modified to account for the possible presence of protection systems (H^*). The procedure to evaluate the modified hazard (H^*) is illustrated in Figure 2.

The relevant parameters which enable to describe a given existing protection system installed along the slope interested by the analysis are: 'design', the 'location' and the 'conditions' of the considered protection work. The 'design' and 'location' parameters describe the system ability to effectively stop the blocks falling along the slope. These parameters are evaluated assuming that the considered protection system is perfect working conditions. These parameters, as illustrated in Figure 2a range from 1 to 5. Value 1 for design (location) represents the optimal condition, that is: the system has been suitably designed (positioned) and is thus able to catch the blocks as predicted by the relevant slope analyses. On the other hand, value 5 represents the worst circumstances.

The 'condition' parameter account for a diminished performance of the protection work owing to its state of maintenance. Values vary from good to problematic (Figure 2b).

Combination of 'design' and 'location' parameters supplies the overall 'utility' of the protection system which decreases from 1 to 5 (Figure 2a).

As depicted in the chart of Figure 2b, the determined 'utility' is combined with the 'condition' parameter providing the 'priority of protection system maintenance'. This parameter describes the actual (i.e. in the real working conditions) system effectiveness. It range from A to E in the sense of decreasing priority. The modified hazard (H^*) is then evaluated according to Figure 2c, by combining the 'hazard of the natural slope' with the 'priority of protection system maintenance'.

According to the procedure, the hazard magnitude can remain unvaried, be reduced or even enhanced owing to the protection system actual effectiveness. A single uncertain parameter (problematic) can itself increase the natural slope hazard (H).

It is therefore apparent that a procedure as such can be successfully applied only if the behaviour of the protection work is thoroughly known.

Suitable numerical analyses can be carried out in order to reduce the uncertainties related to the evaluation of these three parameters, notably the ‘design’ and ‘condition’. A possible procedure is suggested in the following sections, with reference to rockfall protection barriers.

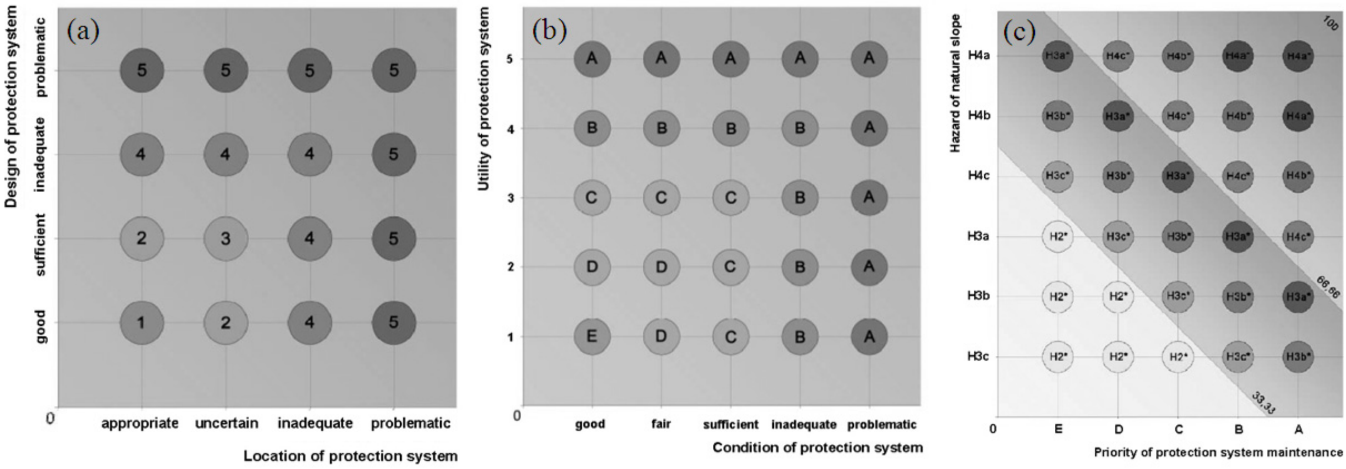

Figure 2. Procedure for the evaluation of the modified hazard H^*: a) chart for the assessment of the protection system ‘utility’ b) chart for protection system ‘maintenance priority’ and c) chart for the evaluation of the modified hazard H^*.

3 DEVELOPMENT OF A DATABASE OF FALLING ROCK PROTECTION BARRIERS

A typical falling rock protection barrier is made of a series of identical functional modules installed in sequence to the desired length. Each functional module generally features an interception structure, kept in position by a supporting structure. Connecting components join the barrier elements and transfer the loads to the foundations.

Protection barriers are designed to intercept and stop blocks moving along a slope in a rockfall event. Traditionally the design capacity is related to the maximum energy possessed by a block which the barrier is capable to arrest.

Several models and types barriers are now available, covering a wide range of capacities. Barriers belonging to different capacity classes typically feature diverse structural components. Customarily, all barriers types are grouped in two main categories. Those belonging to low energy classes are named semi-flexible and those of higher energy classes flexible (Peila et al., 2008), but barrier with intermediate characteristics are frequently encountered as depicted in Figure 3.

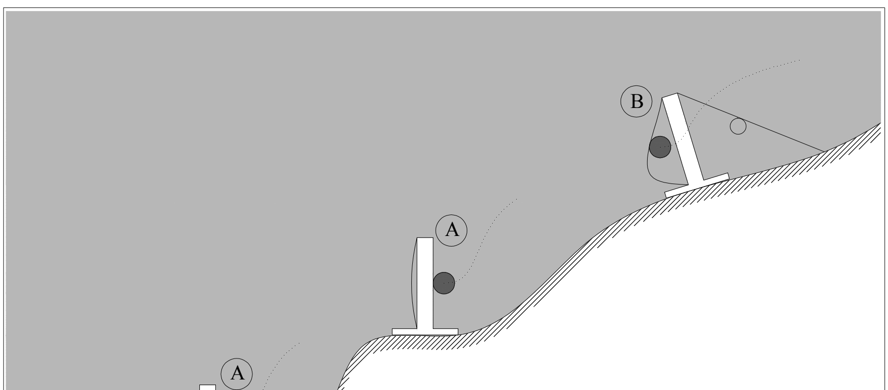

Figure 3. Falling rock protection barrier: scheme of relevant typologies of falling rock protection barriers: A semi-flexible, B flexible.

Although some plastic deformations are likely to occur, semi-flexible barriers mostly deform elastically, under the impact of block having low to medium impact energies. The capacity is thus related to their ability to catch and stop a block without undergoing rupture in the system and system components. Conversely, flexible barriers typically dissipate the high impact energies by developing large plastic deformation: the greater the barrier capacity, the higher its plastic compliance. For these barriers the deformation should be also kept within working levels. As it can be observed in Figure 3, where a photographic example of each barrier category is given, when assembled on site, each barrier becomes a unique item, though retaining the principal features of its capacity class.

Basic information on the barriers of the Autonomous Province of Bolzano, can be now found in VISO, a thorough inventory of the protection works now installed within the province area. With reference the specific hazard event and threatened items, passive systems such as ditches, wire nets, earth dams, sheds, and falling rock protection barriers are registered within the inventory. Data have been mostly acquired by direct inspections carried out over the law few years.

Within the inventory, position, typology and principal dimensions of each protection work are given, along with a relevant photographs and remarks on the state of maintenance.

3.1 *Falling rock protection barrier description and classification*

These data have been recently conveniently integrated, addressing a more precise description of the geometrical and mechanical properties of the structure and principal structural components.

Additional information were mostly acquired from documentation supplied from agencies in charge to protect the relevant road stretches and manufacturer companies. Documents include technical reports, design reports and drawings. These data enable to identify the most frequently occurring barrier types. Within the Province’s territory, approximately thirty barrier types were identified: more than twenty among those having the higher energy absorption capacity and less than ten among those belonging to the low and medium energy classes. A thorough description of the typical functional module of the identified barrier type was carried out according to the available documentations. In particular, the interception structure, the supporting structure, the connecting components, including ropes, cables, clamps an energy dissipating device and internal and external restraints were described in details. Also, if available, data of full-scale tests of prototypes, as well as all the design drawings were conveniently analyzed and relevant information were included in the database.

A procedure was then carried out in which the falling rock protection barriers formerly inserted in VISO were grouped according the relevant barrier type.

Figure 4a shows a barrier made of a series of the typical functional module of barrier type ANAS as inventoried in VISO. The schema of the typical functional module is found in Figure 4b, where information are also given on the principal structure components. For this barrier type, no information are available on the nominal behaviour or energy class. Nonetheless, barrier type ANAS can be described as semi-flexible.

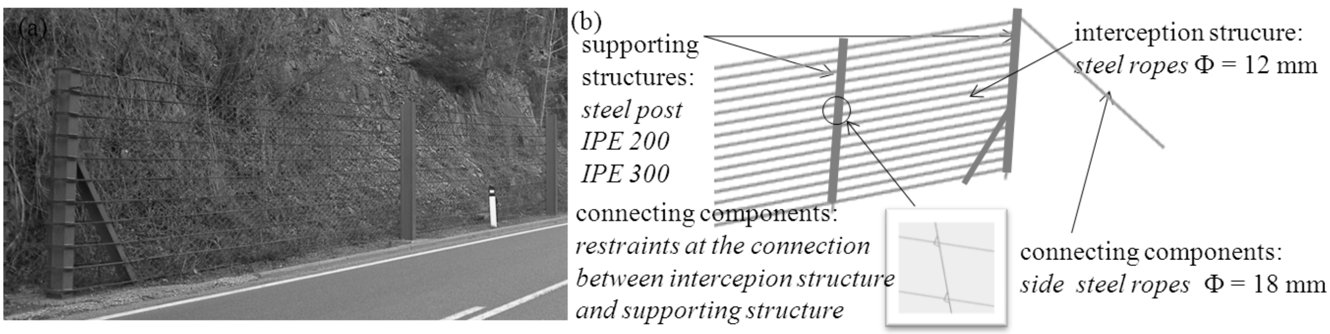

Figure 4. Example of falling rock protection barriers installed in the Autonomous Province of Bolzano: a) barrier ss38_12_1 belonging to type ANAS and b) scheme of the functional module of barrier type ANAS.

Figure 5a shows one of the VISO flexible falling rock protection barrier. The barrier is one of high energy absorption capacity which features a set of the functional modules of barrier type PT_B750 described in the drawing of Figure 5b. For this barrier type a comprehensive technical report documenting the barrier behaviour under impact was available. In the technical report details of results of full scale tests carried out on PT_B750 prototypes were included assessing the barrier capacity to arrest blocks having energies up to 750 kJ.

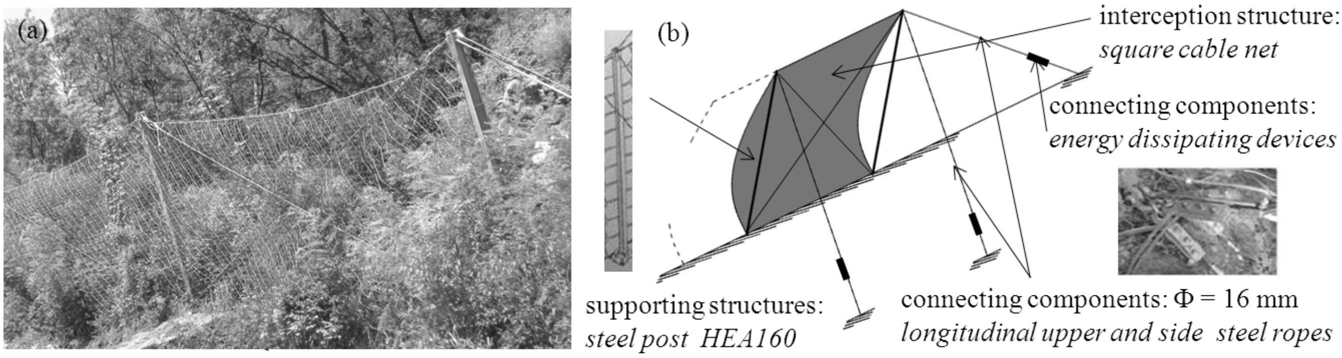

Figure 5. Example of falling rock protection barriers installed in the Autonomous Province of Bolzano: a) barrier 12_5_GR_008/014 belonging to type PT_B750 and b) scheme of the functional module of barrier type PT_B750.

With reference to flexible and semi-flexible systems, Figure 6 provides the number of occurrences of each barrier type divided by the total number of barriers (approximately 700). The name given to the barrier type includes, when available: the manufacture company denomination, the capacity and the date in which the nominal capacity was assessed by full-scale testing and then placed on the market. For instance, barrier type PT_B750, depicted in Figure 6 has a nominal capacity of 750 kJ. The capacity was assessed in 2000 by full scale testing of barrier prototypes. Among all the flexible and semi-flexible barrier types barrier PT_B750 is the most frequently occurring.

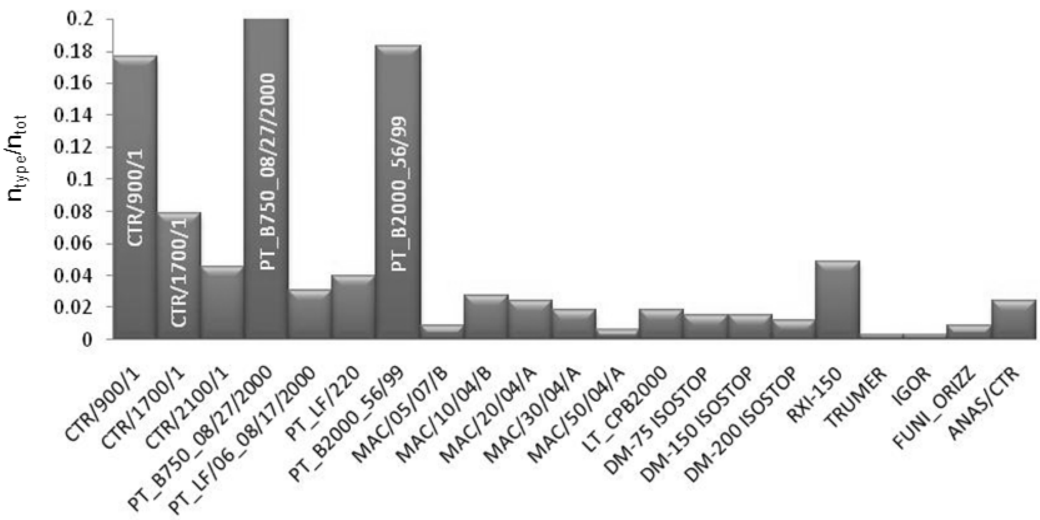

Figure 6. Principal types of flexible falling rock protection barriers within the Autonomous Province of Bolzano.

4 NUMERICAL STUDY OF FALLING ROCK PROTECTION BARRIERS

The data collected in the database provide the starting point for a numerical study of the barriers described in it. To the scope, the commercially available computer program ABAQUS/Explicit v. 6.9 (Hibbit et al. 1997) has been employed as it has been shown it is especially suitable to perform and solve high speed dynamic events (Cazzani et al. 2002, Mentani, 2010).

The preliminary FE study herein presented, addresses the three-dimensional, non linear, dynamic response of the two barrier types described in the previous section. The study is carried out in analogy with a well established full-scale testing procedure (Peila, 1999, Geber, 2001, Gottardi and Govoni, 2010) which is generally used to assess the capacity of a falling rock protection barrier to effectively stop blocks having kinetic energy up the design level. Such procedure has been historically used as a design tool for rockfall fences (Higgins, 2003) and it has lately been applied to flexible barriers in an extensive manner, becoming a mandatory step in the process of CE marking of barrier having energy absorption capacity higher than 100 kJ (EOTA, 2008).

Full-scale impact test are generally carried out at a suitable test site onto samples of falling rock protection barriers consisting of three functional modules (i.e. three spans). At the test site a concrete test block is accelerated to impact, with speed known both in intensity and direction, the centre of the falling rock protection barrier prototype installed at some inclination to a test rock wall.

During the test, relevant quantities, such as the barrier elongation and the forces on the foundations are generally recorded with time. Further information on testing details are comprehensively found in Peila et al. (2006).

Noting that the procedure assesses the barriers response with sole the reference to kinetic energy parameters, although other parameters might significantly affect the barrier response (Cantarelli et al., 2008), the FE study was developed following these instructions.

In the following sections, details on the numerical modelling are illustrated along with briefly commented preliminary results.

4.1 *Details on the numerical modelling: barrier types and testing procedures*

Two barrier types were modeled, which were selected as representative of different capacity classes: the ANAS and the PT_750. Description of these barrier types were provided in Section 3, and relevant pictures were provided in section 3 and Figures 4 and 5.

Following the above described experimental procedure numerical models were made up of three functional modules.

In Figure 7, the three functional modules model of barrier ANAS is shown with nodes numbered from 1 to 10. At node 1 to 6 the barrier was connected to the ground through the two side cables and four posts. All dofs were restrained at these 6 nodes (black dots).

With reference to the barrier structural components illustrated in Figure 4b, steel posts were modeled employing two-nodes beam elements having the relevant, IPE, cross sectional area. One dimensional two-nodes truss elements, with no flexural rigidity and zero compression axial load limit were employed to describe the behaviour of all the steel ropes which form the interception structure as well as the side cables. Sections were assigned according to the actual elements cross sectional area. For all the elements a bilinear, elastic-plastic behaviour was assumed. Particular attention was focused on the modelling of the system connecting elements such as the ropes connections to posts.

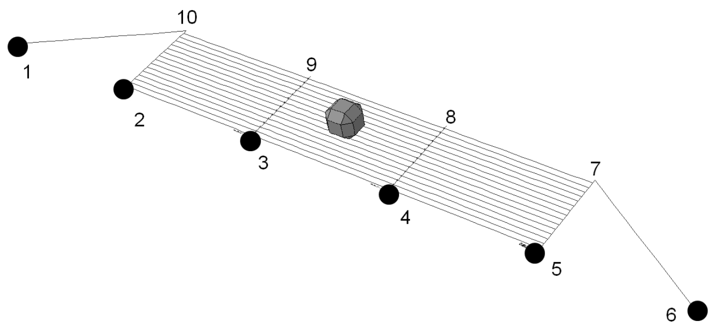

Figure 7. Three functional modules FE model of the ANAS barrier.

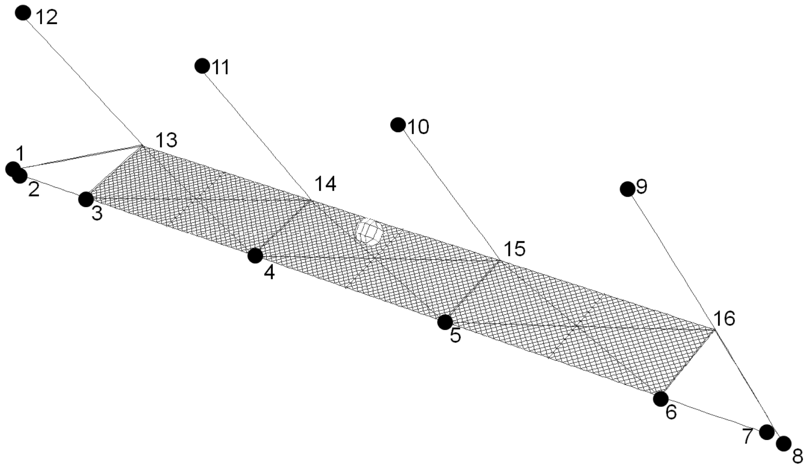

Figure 8. Three functional modules FE model of the PT_750 barrier.

In Figure 8, the three functional modules FE model of barrier PT_750 is shown with nodes numbered from 1 to 16. At node 1 to 12 the barrier was connected to the ground through the side cables, the longitudinal lower ropes, uphill cables and four posts. Connections of the structure to the ground were modeled at these point as cylindrical hinges.
With reference to the barrier structural components illustrated in Figure 4b, two-nodes beam elements were used for the posts. A mesh of one-dimensional two-nodes truss elements was used to model the interception structure. Trusses were also employed for the side and uphill cables. Sections were assigned according to the actual elements cross sectional area. For all the elements a bilinear, elastic-plastic behaviour was assumed.

As mentioned above, no information on the structural behaviour or indication on the energy class were available for barrier type ANAS. The numerical analyses were carried out following widely used full-scale tests procedures at vertical drop test sites (Gerber, 2001, Gottardi and Govoni, 2010). In the procedure a three functional modules barrier prototype, installed normal to a vertical rock wall is impacted vertically by a concrete test block.

In the FE analysis the block was modelled with a three-dimensional deformable body shaped as a polyhedron. By varying the block velocity, the simulation were performed at 25, 50, 75 and 100 kJ, in order to observe the barrier response to increasing values of kinetic energies up to admissible stress values.

Results of full-scale tests on prototypes were, instead, available for the PT_750. Experiments were carried out at an inclined test site (Peila, 1999). Data recorded in the tests were the maximum barrier elongation and the residual height. The FE study was carried out in order to replicate the full-scale tests as close as possible. A model of three functional modules was developed and installed according to the test site geometry as depicted in Figure 8. The barrier model was then subjected to one single launch of a block having kinetic energy higher than 750 kJ.

4.2 *Results*

In Figures 9 to 10 preliminary results of the FE dynamic analyses on the models of barrier types ANAS and PT_750 are provided qualitatively in term of stress and structure deformed shape.

In Figure 9 the data obtained by the numerical simulation carried out at 100 kJ on the ANAS barrier are presented. The Figure depict the barrier at the instant of the test at which the maximum barrier deformation occurred, approximately at 0.15 s since the start of the analysis. The barrier response is depicted by its deformed shape. Maximum non-admissible tensile stress were reached within the truss element involved by the impact (darker gray lines).

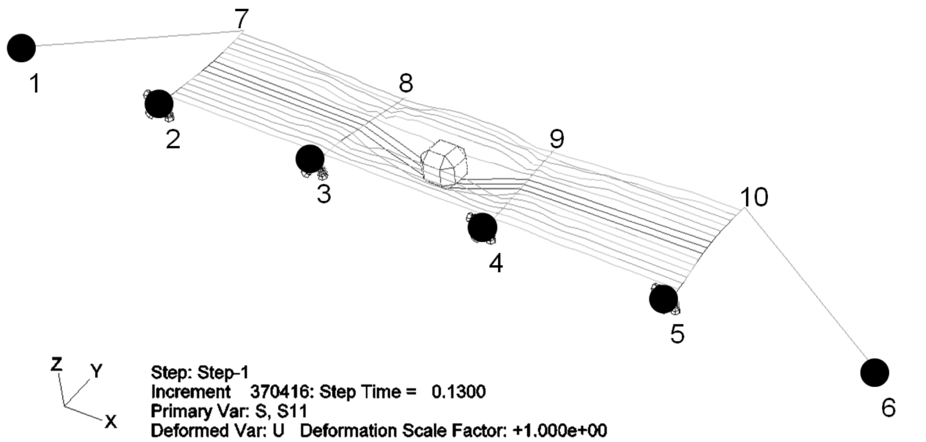

Figure 9. Deformed shape and qualitative stress distribution within the model of the ANAS barrier type at the maximum elongation during 100 kJ analyses. Time = 0.15s.

In Figures 10 the principal results of the analysis carried out on the PT_750 barrier are provided at three different instant at which the maximum elongation has been reached (0.24 s). Frames provide a qualitative assessment of the barrier behaviour during the impact. Results on barrier deformation substantially agree with the experimental, both in terms of maximum displacement (approximately 3m) and time to reach it. Furthermore all stresses were found to be within the admissible limit, assessing the model capacity of describing the barrier behaviour in testing conditions. The model thus enables to provide reliable predictions on other data such as the time histories of the forces at the foundations.

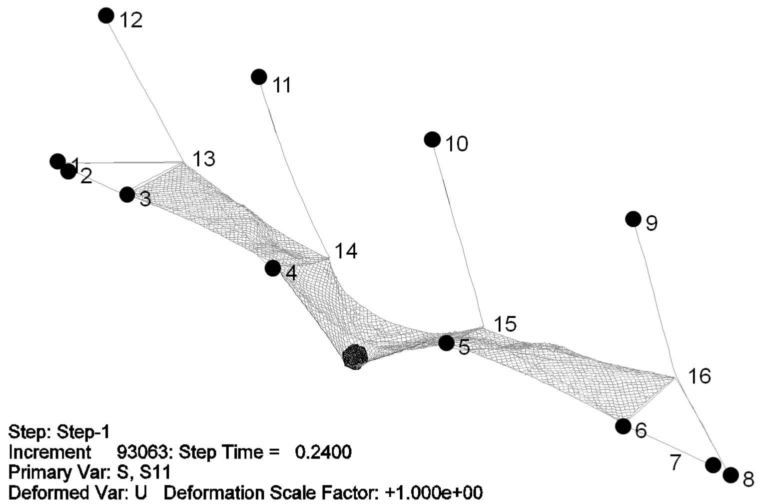

Figure 11. Deformed shape and qualitative stress distribution within the model of the PT_750 barrier type. Time = 0.24s.

5 CONCLUDING REMARKS

The paper has presented the preliminary results of a study on diverse types of falling rock protection barriers installed within the Autonomous Province of Bolzano. The study forms part of the activities of European project PARAmount (imProved Accessibility, Reliability and safety of Alpine transport infrastructure related to MOUNTainous hazard in a changing climate) and particularly addresses a method to evaluate the effects of passive measures against rockfall toward risk mitigation. In the paper the development of a database of the falling rock protection barriers at present installed within the Province is described. The database is aimed to collect the data necessary to a numerical study of the most frequently occurring barrier types. The scope of the numerical study is to produce information on the barrier nominal response in dynamic conditions. Numerical models then provide the data to the description of the nominal behaviour of the protection system during an impact. They can also be used to investigate the actual barrier response if they are suitable modified to accommodate the on-site arrangement, positioning and state of maintenance.

REFERENCES

Cantarelli G., Giani G. P., Gottardi G., Govoni L. (2008) Modelling falling rock protection fences. 1st World Landslide Forum, Tokyo, Novembre 2008.

Cazzani A., Mongiovì L., Frenez T. (2002) Dynamic finite element analysis of interceptive devices for falling rocks. Int. J. Rock Mech. Min. Sci. 39 (3) 303–321.

Corominas J., Copons R., Moya J., Vilaplana J. M., Altimir J., Amigo J. (2005). Quantitative assessment of the residual risk in a rockfall protected area, Landslides, 2 (2005) 343-357

EOTA (2008) Guideline for European technical approval of falling rock protection kits (ETAG 027). February 2008, Brussels.

Fell, R. & Hartford, D. (1997) Landslide risk management. Proc. of the International workshop on landslides risk assessment, Honolulu, 19-21 February 1997, Balkema Rotterdam, pp. 51-110.

Gerber W. (2001) Field testing of falling rock protectionprotection barriers a comparison between inclined ropeway and vertical crane testing. Swiss Agency for the Environment, Forests and Landscape (SAEFL) and the Swiss Federal Research Institute WSL. August 17th 2001. Birmensdorf.

Giani G. P. (1992) Rock slope stability analysis. Balkema, Rotterdam, NL

Gottardi and Govoni (2010) Full scale modelling of rockfall protection barriers, Rock Mech. Rock Engng. 43 (2010), pp. 261-274.

Hibbitt, Karlsson and Soresen Inc. 1997. ABAQUS Theory manual – Version 6.9. Pawtucket, RI.

Higgins J. D. (2003) Recommended procedure for the testing of rock-fall barriers. AASHTO Technical Report, Washington.

Lee, E.M. & Jones, D.K.C. (2004) Landslide risk assessment. Thomas Telford, 2004.

Mentani, A. (2010). Numerical non linear modelling of the response of a rockfall protection barrier to impact loading, Master Thesis, Advisor Prof. G. Gottardi, Bologna 2010 (in Italian)

Peila D., Pelizza S., Sassudelli F. (1998) Evaluation of behaviour of falling rock protection restraining nets by full-scale tests. Rock Mech. Rock Engng. 31 (1998) 1-24.

Oggeri C. and Tosco P. (2005) Identificazione del rischio per fenomeni di caduta massi, GEAM., 2005, Vol. 1, 23-32.

Peila D, Oggeri C, Baratono P (2006) Barriere paramassi a rete, interventi e dimensionamento. GEAM Quaderni di studio e documentazione 25, Torino.