DOI: 10.4408/IJEGE.2013-06.B-19

HAZARD ASSESSMENT OF A POTENTIAL ROCK AVALANCHE IN SOUTH TYROL, ITALY: 3D MODELING AND RISK SCENARIOS

Giulia BOSSI, Simone FRIGERIO, Matteo MANTOVANI, Luca SCHENATO, Alessandro PASUTO & Gianluca MARCATO

CNR-IRPI – National Research Council of Italy, Research Institute for Hydro-Geological Hazard Protection - Padova, Italy

ABSTRACT

A large DSGDS (Deep-Seated Gravitational Slope Deformation) which extends on an area of 3.75 km^2 affects the southwest flank of Mount Ganderberg some 40 km north of Bolzano. The gravitational sagging of the slope is generating a wide field of tension cracks in the crown area where a rock slab of about 800.000 m^3 shows clear precursory signs of possible detachment.

In 1401 a rock avalanche detaching from the same area dammed the Passer River thus creating a 35 m deep lake which through sequential breaching caused many casualties in the villages downstream. Using geomorphological survey and historical analysis it was possible to estimate the volume of the landslide deposit in 2×10^6 m^3.

In this study the historical event is back-analyzed using the 2D code DAN-W in order to select the proper soil parameters to use in the modelling of the present potential rock avalanche. Then a 3D modelling is carried out using DAN3D software to evaluate the run-out scenario and the shape of the natural dam. Owing to the relevant discharge of the Passer River, a 2×10^6 m^3 lake might be quickly filled. This can cause the breaching and subsequent collapse of the landslide dam with great risk and potentially heavy damages for the downstream population.

***Key words**: landslide hazard, 3D modeling, runout, risk scenarios, Ganderberg*

INTRODUCTION

The prediction of the landslide runout is of crucial importance for risk assessment, especially in densely populated valleys. As the mechanisms of fast landslide such as rock avalanches is not completely understood, mostly because of the numerousness of the variables involved in the process (Evans *et alii,* 2006), the task of defining the related hazard is still problematic. Moreover, especially in Alpine environments, river damming is a potential scenario which implies considerable threats for the nearby population due to backwater impounding and catastrophic dam-brake waves (Costa & Schuster, 1987). To properly estimate this consequential hazard (Korup, 2005) an hypothesis on the geometry of the deposit should be made; several approaches both empirical (Nicoletti & Sorriso-Valvo, 1991; Corominas, 1996) and analytical (Savage & Hutter, 1989; Hungr, 1995) have been proposed in the past literature.

Runout models are regularly used for debris flow but modelling potential rock avalanches is far from current practice (Crosta, 2006). The selection of the correct soil parameters to use in the model is the main constraint; in doing so the best approach seems to be the retroactive simulation of a past event in the study area (Hungr, 1996; Willenberg, 2009).

The present paper deals with the assessment via numerical model of a potential rock avalanche in South Tirol. A similar phenomenon, dating 1401, occurred in the same site forming a natural dam and consequently a large lake, about 1 km long. Since the downstream settlements were repeatedly affected by outburst debris flows due to the collapse of sections of the dam until the 18th century (SCHUSTER, 2000), our goal is to evaluate the possibility of the formation of a new landslide dam and to assess the associated risk

GEOGRAPHICAL SETTING

A large DSGDS (Deep-Seated Gravitational Slope Deformation) of 3.75 km^2 affects the southwest flank of Mt. Ganderberg (46°51'27''N, 11°10'26''E) some 40 km north of Bolzano, in the Passeiertal, near the border with Austria (Fig. 1).

With an estimated 150 m deep shear surface, it stretches from the 2330-2450 m a.s.l. of Mt Ganderberg and Mt Kreuzjoch down to the Passer River at 1170 m a.s.l (Fig. 1). The DSGSD is concave in the upper part, where a huge ridge borders the landslide crown, flat in the center and bowed at the toe; therefore it can be considered in the final stage (PASUTO & SOLDATI, 1990) (Fig. 2).

The upper Passer River basin, closed at the toe of the Ganderberg landslide, covers an area of 85 km^2 with maximum altitude of 3400 m. The river is characterized by an alpine regime with high rate of flow in spring during snowmelt that has reached several times a peak discharge of 42.5 m^3/s.

The elements at risk in the study area are the National Road n. 44bis, which crosses the landslide, and the small settlement of Hahnebaum which lays, in the southern sector, near the toe of the DSGSD. Moreover, in case of landslide damming of the Passer River, the risk would spread along the stream for several kilometres as resulted from the past events.

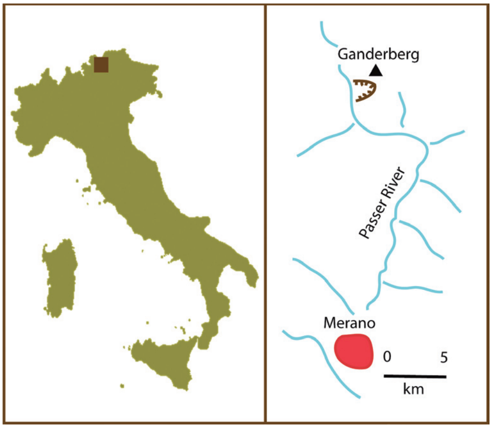

Fig. 1 - Location of the study area

PAST RECURRENCE OF LANDSLIDES

Historical records (WALCHER, 1773) report that in 1401, due to the collapse of a rock slab from the north-west ridge of Mt Ganderberg, the Passer river was dammed forming a 35 m deep lake named Kummersee (Lake of Grief).

During the first years the lake overtopped the dam but the stability of the deposit was not endangered. Then in 1419 the dam was breached for the first time causing rapid erosion of the deposit and a sudden sediment-laden flood that reached the town of Merano, which lies 26 km downstream, causing 400 casualties. Other catastrophic bursts followed several times in the ensuing years, mostly after autumnal heavy rainfall events; in particular in 1503 the flood was so severe that chronicles report that the city walls of Merano were shattered (EISBACHER & CLAGUE, 1984).

The lake eventually disappeared in the 18th century but the 1.5×10^6 m^3 remnant of the former dam still lays on the opposite slope. The dam and the sedimentation in the lake have significantly influenced the longitudinal profile of the Passer River, inducing locally a steep slope that has been regulated in recent years by several check dams.

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

In the study area mainly metamorphic units of the Australpine basement complex outcrop, that is a predisposing geological framework for DSGSD (HUTCHINSON, 1988). Besides, the unremitting movements of the DSGSD lead to the progressive weakening of the rock mass inducing collateral phenomena like rock avalanche, debris flow or secondary slides (AGLIARDI, 2001).

Silver-gray shining mica-schist outcrops at the crown of the landslide in the north-east ridge where minor signs of deformation are found. However in Mt Ganderberg paragneiss ridge transverse cracks and trenches are extensively widespread. The sagging of the DSGSD generates locally steep slope gradients with high potential energy; distinct secondary movements are recognizable and mostly influenced by the attitude of the several joints affecting the bedrock. In particular the rock slab in Fig. 3 is backtilted and widely fractured. The contour of the slab has been outlined through a GPS survey; thus, considering the intersection of the rock discontinuities of 230/80 and 165/45 dip direction, it was possible

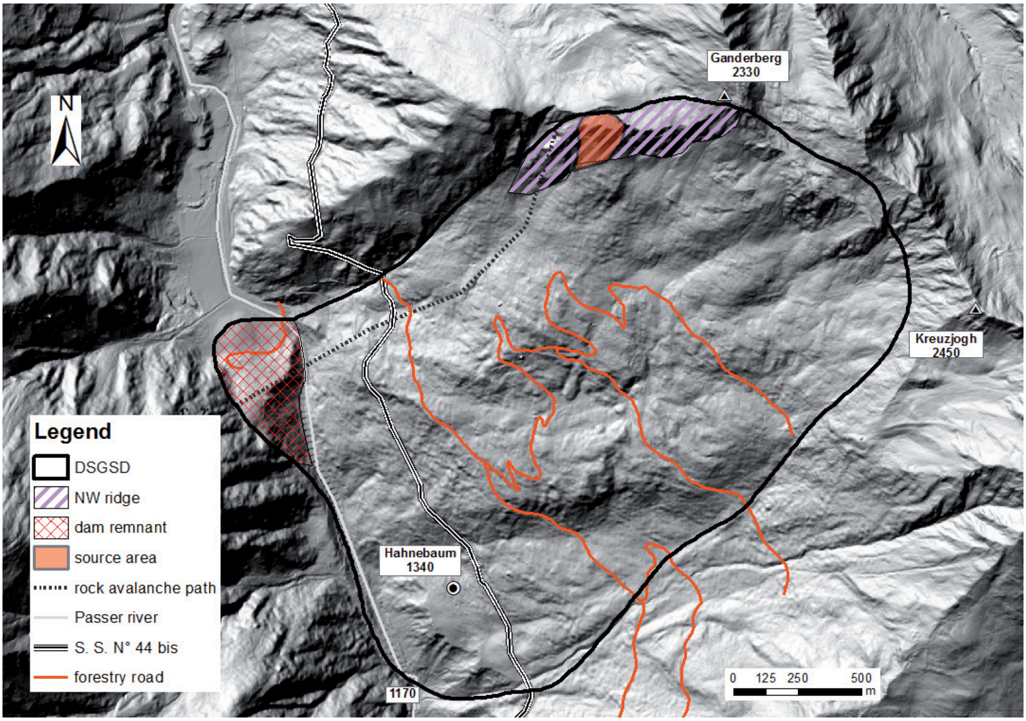

Fig. 2 - Shaded relief of the DSGDS with highlighted the remnant of the 1401 landslide dam

to delineate a 800,000 m^3 unstable rock wedge. In case of detachment, this block is likely to evolve into a rock avalanche, as it happened in the past, since there is no confinement or topographic discontinuity that could stop it before it reaches the valley bottom.

MODELLING

BACK ANALYSIS OF THE 1401 EVENT

A dynamic analysis of the runout for the 1401 event was carried out in order to determine the parameters to use in the 3D modeling of the present potential rock avalanche (Bossi *et alii*, 2011).

Considering the orientation of the discontinuities and the data from a GPS survey through a geomorphological analysis it was possible to reconstruct the contour of the former rock slab with a 3D software (Surfer 9, Golden Software, Golden, CO, USA). The total volume of the detached rock mass was estimated as $2{\times}10^6$ m^3.

The model was calibrated on the historical records of the event and on the basis of geomorphological surveys of the deposition area. The former river bed profile has been derived appraising the average slope of the Passer River between the stretches that were not affected by the event. Moreover the former talweg was likely to flow in the middle of the valley as it is in its other reaches, even though nowadays it circles the 1401 landslide dam remnant. Furthermore in the area a small debris slide was found on the left bank clearly denoting a relatively recent modification of the valley morphology, the trigger of such landslide being evidently toe erosion since the slope is steeper than nearby.

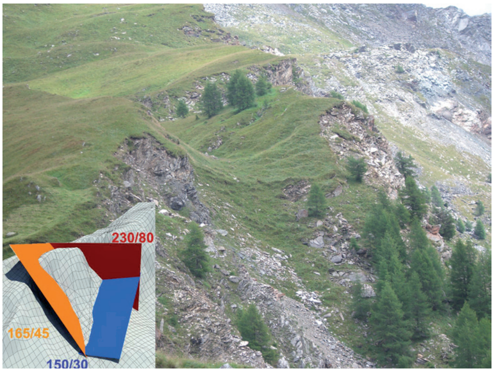

Fig. 3 - View of the unstable rock slab. The arrangement of the joint planes and the former vertical movement of the rock block (beside the lesson learnt from previous events) pose a distinct hazard due to the potential triggering of a rock avalanche

Due to the narrowness of the alpine valley the shape of the deposit can be classified as "strong impact" (Hewitt, 2002): the avalanche material climbed upward on the opposite slope, like backwash. The phenomenon is called "brandung" in German (Heim, 1932) and it causes great energy dissipations. Therefore the typical long runout of rock avalanches, due to the impact on the facing mountainside, resulted in a concentrated accumulation of material. In the surroundings of the rock avalanche deposit, regions altered by the pressure and temperature (frictional breccia, partial melting) are found. On the base of petrographic investigations these dark beds came probably to being by heating due to the friction of the strongly mylonitised and at least partially liquated rocks (Egger, 2001).

Considering the usual geometry of "brandung" the volume of the former deposit has been estimated in 3.5×10^6 m^3; the increasing in volume (up to 75%) since detachment is ascribed to erosion and to the fragmentation of the rock mass.

The modelling was performed using DAN-W (OHGRI, West Vancouver, BC, Canada), a pseudo-3D code in which the flow depth reflects the amount of spreading expected for the flow path. A frictional model was selected since the Voelmmy rheology did not reproduce well the "brandung" dynamic. After several simulations a good fit was established with a bulk friction angle of 16° for the material, which is low but it reproduces the peculiar mobility of rock avalanches and it is in accordance with several other authors findings (Hungr, 1995).

3D MODELLING, RISK SCENARIOS

The 3D simulation was performed with DAN3D software (Hungr, 2009). DAN3D is a meshless Smoothed Particle Hydrodynamics (SPH) code which use an integrated two-dimensional Lagrangian solution. The rock mass is discretize in numerous particles that flow forced by topography on the basis of a selected rheology.

The shape of the unstable slab was reconstructed geometrically in 3D, considering the orientations of the joints and the internal friction angle of the rock mass (Fig. 4). The Digital Terrain Model with a resolution of 2.5 m was acquired from the regional authorities and it was derived by LiDAR survey performed via helicopter. The data from the best-fit back-analysis were used for the soil input parameters.

The outputs show that if the unstable rock slab collapse it would form a 20 meters high deposit on the valley bottom already narrowed by the 1401 landslide dam remnant (Fig. 5). The accumulated material would form a dam which could generate a 15 meters deep lake; it has been calculated that such lake would have a maximum volume of 2×10^6 di m^3, reaching the length of 1.5 km (Fig. 6). The lake would inundate a quarry and a long portion of a local road which is the only way to reach the village of Corvara in Passiria. Nevertheless the major risk would be for the population living downstream since the dam failure could result in a dramatic outburst flood.

As the potential deposit is large and elongated the hazard of failure by piping is negligible. On the other

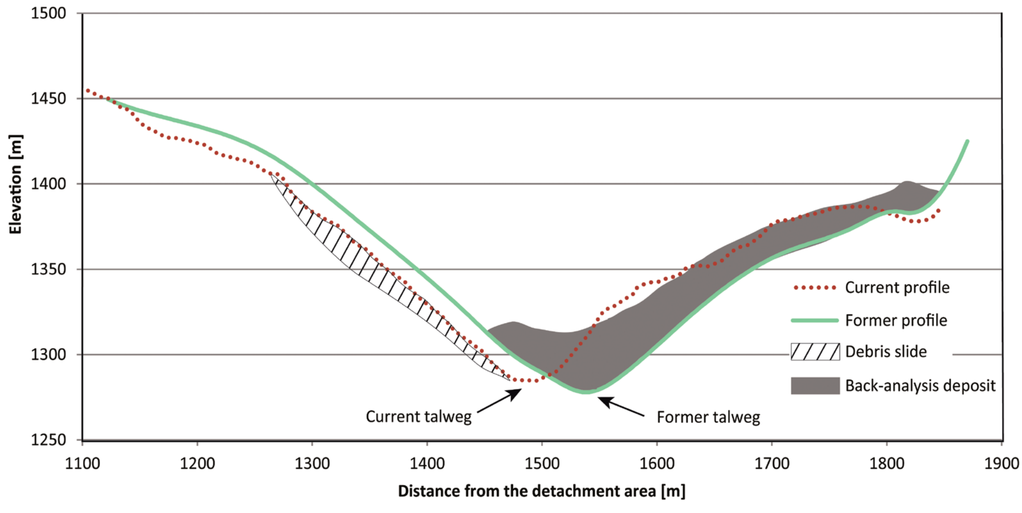

Fig. 4 - Profile of the landforms on the Passer River banks at the cross-section with the former deposit

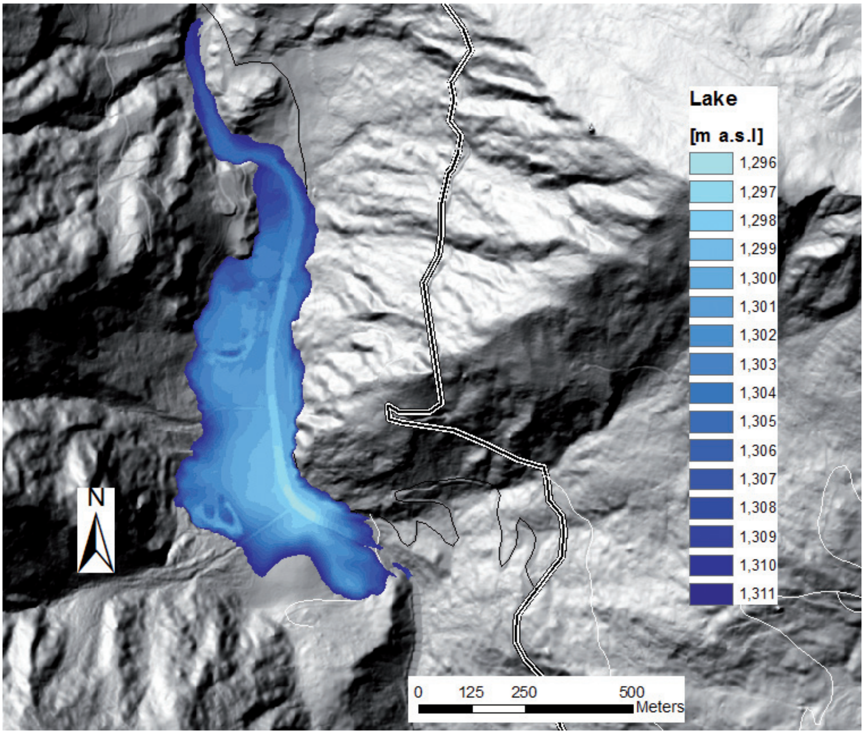

Fig. 6 - Flooded area

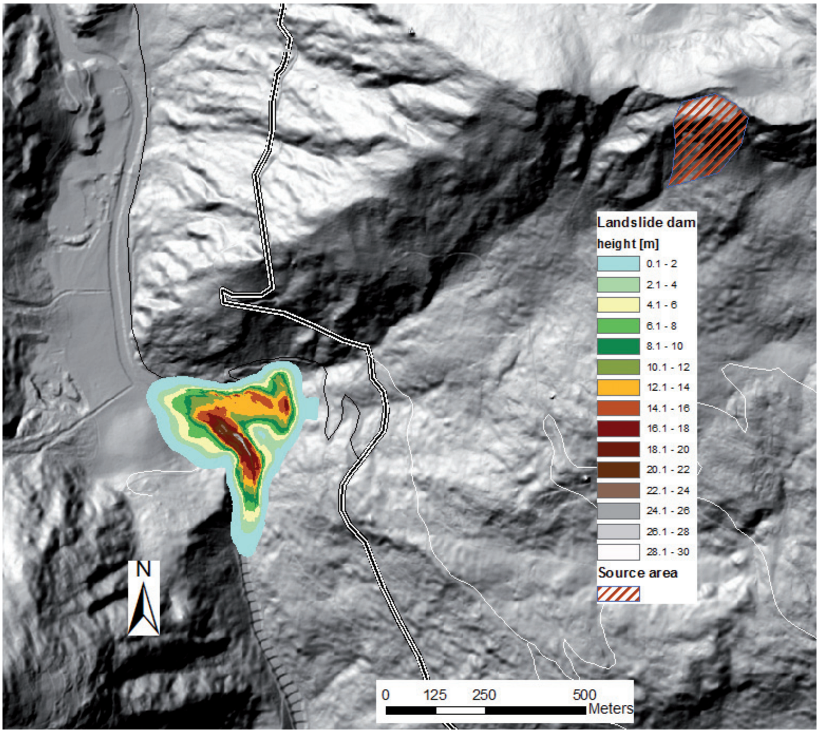

Fig. 5 - Area and thickness of the landslide dam obtained through the DAN3D simulation

side the threat of headward and downward erosion is significant as the deposit would likely be composed by loose materials owing to the mechanics of rock avalanches. Moreover, due to the size of the impounded area and in high water discharge periods the collapse of the landslide dam could be very fast.

A statistical analysis of the historical records of the discharge of the Passer River show that in the basin the outflow reaches 500 l/s km^2 every 10 years. This happens especially in springtime when to the seasonal rains the hydric contribution of snowmelt is added. At the Ganderberg outlet the discharge in these conditions is 42.5 m^3/s, therefore the lake could be filled in less than a day leaving a small span of time to implement civil defence emergency plans.

DISCUSSION

The main purpose of the present study was to provide to the public administration in charge of development the Civil Defence Plan an effective tool to evaluate the hazard and manage the risk induced by the DSGSD affecting Mt. Ganderberg. In doing so an integrated approach combining modelling and monitoring activities has been selected. The analysis carried out indicates that the hazard related to the possible detachment of an 800.000 m^3 unstable rock slab from Mt. Ganderberg is relevant. The rock mass could collapse and evolve as a rock avalanche damning the Passer River and creating a 2×10^6 di m^3 lake.

To mitigate and manage the risk for the population of the valley a real time monitoring system has been designed and installed in order to assess the magnitude of displacement and the rate of movement. A control unit able to collect and storage the data as well as to transfer them via GPRS to the headquarter of CNR-IRPI in Padova, is located in a safe position outside the detached area. Across the most evident cracks six extensometers (± 0.01 mm accuracy) were installed along with a geophone for acoustic emissions detection. This system helps in assessing the trigger processes that can induce significant movements and allows the definition of the dynamic of the rock mass therefore controlling the possibility of secondary movements like partial toppling. Besides, a long-base wire extensometer was installed because it could be useful in measuring large displacements before the final collapse. In order to forecast the failure occurrence the collected data will be analysed through a Saito & Fukuzono equation analysis (Fujisawa *et alii*, 2010). This procedure will be automatically implemented in the system and will represent an early warning system thus mitigating the risk associated with the phenomenon.

Once the back-analysis has been carried out the modelling activities provided a range of possible risk scenarios to be included in the civil defence emergency plan. The data gathered from the monitoring and the modelling are therefore mutually dependant and their integration allow the local authorities to periodically update the plan, according with possible new risk scenarios. In fact, if the monitoring data indicate the possibility of partial collapse the model will be easily updated because the soil parameters to use are already known though the back-analysis. The flexibility of the approach is a crucial element since the modelling activity results in a dynamic tool for the generation of future risk scenarios. This seems to be of paramount importance in creating an effective risk management plan helping the public authorities in emergency phases.

ACKNOWLEDGEMENTS

The research has been founded by the Interreg project MONITOR II, financed by the South East Europe Programme 2007-2013. This work has been also partially funded by the Fondazione Cassa di Risparmio di Padova e Rovigo within the Research Project “SMILAND”.

REFERENCES

Agliardi F., Crosta G. & Zanchi A. (2001) - *Structural constraints on deep-seated slope deformation kinematics*. Engineering Geology, **59:** 83-102.

Bossi G., Mantovani M., Marcato G., Pasuto A., Mair V., Nössing L., & Stefani M. (2012) - *The Ganderberg landslide (South Tyrol, Italy): Residual hazard assessment and risk scenarios.* Proc. of the 11th Int. and 2nd North American Symp. on Landslides and Engineered Slopes. Landslides and Engineered Slopes: Protecting Society through Improved Understanding, Banff, Canada, 763-768.

Corominas J. (1996) - *The angle of reach as a mobility index for small and large landslides.* Canadian Geotechnical Journal, **33:** 260-271.

Costa J.E. & Schuster R.L. (1987) - *The formation and failure of natural dams.* US Geological Survey, Open-File Report 87-392.

Crosta G.B., Chen H. & Frattini P. (2006) - *Forecasting Hazard Scenarios and implications for the evaluation of countermeasure efficiency for large debris avalanches.* Engineering Geology, **83:** 236-253.

Egger H. (2001) - *Ingenieurgeologische Untersuchung des Gan-derberg Talzuschubs und der Seehofer Bergsturzmasse.* Diplomarbeit, Institute of Geology and Mineralogy Friedrich-Alexander University.

Eisbacher G.H. & Clague J.J. (1984) - *Destructive mass movements in high mountains: hazard and management.* Geological Survey of Canada, 84-16

Evans S.G., Scarascia Mugnozza G., Strom A.L., Hermanns R.L., Ishuk A., & Vinnichenko S. (2006) - *Landslides from massive rock slope failure and associated phenomena*. Landslides from Massive Rock Slope Failure, Springer, Netherlands, 3-52.

Fujisawa K., Marcato G., Nomura Y. & Pasuto A. (2010) - *Management of a typhoon-induced landslide in Otomura* (Japan). Geomorphology, **124**: 150-156.

Heim A. (1932) - *Dersturz und Menschenleben (Landslides and Human Lives)*. BiTech Publishers Ltd, Vancouver.

Hewitt K. (2002) - *Styles of rock avalanche depositional complex in very rugged terrain*, Karakoram Himalaya, Pakistan. In: Evans S.G. & Degraff J.V. (2003, eds.) - C*atastrophic Landslides: effects, occurrence and mechanisms, Reviews in Engineering Geology*. Geological Society of America, Boulder, Colorado, 345-78.

Hungr O. (1995) - *A model for runout analysis of rapid flow slides, debris flows and avalanches*. Canadian Geotechnical Journal, **32**: 610-623

Hungr O. & Evans S.G. (1996) - *Rock avalanche runout prediction using a dynamic model.* Proc. 7th Int. Symp. on Landslides, Balkema, Rotterdam, 1: 233-238.

Hungr O. & McDougall S. (2009) - T*wo numerical models for landslide dynamic analysis.* Computers & Geoscience, **35**: 978-992.

Hutchinson J.N. (1988) - *General Report: Morphological and geotechnical parameters of landslides in relation to geology and hydrogeology.* Proc. 5th Int. Symp. on Landslides, Rotterdam: Balkema 1: 3-35.

Nicoletti P.G. & Sorriso-Valvo M. (1991) - *Geomorphic controls of the shape and mobility of rock avalanches.* Geological Society of American Bulletin, **103**: 1365-1373.

Pasuto A. & Soldati M. (1990) - *Some cases of deep-seated gravitational deformations in the area of Cortina d'Ampezzo (Dolomites). Implications in environmental assessment.* Proc. of the European experimental course on geomorphology applied to environmental risk in man's impact on the Dolomites, **2**: 91-104.

Savage S.B. & Hutter K. (1989) - *The motion of a finite mass of granular material down a rough incline.* Journal of Fluid Mechanics, **199**: 177-215.

Schuster R.L. (2000) - *Outburst debris-flows from failure of natural dams.* In: Wieczorek G.F. & Naeser N.D. (eds.) - *Debris-Flow Hazard Mitigation: Mechanics, Prediction and Assessment*. Bakelma, Rotterdam, 29-42.

Walker J. (1773) - *Neue Nachrichten von den Eisbergen in Tyrol.* Kurzböck, Wien.

Willenberg H., Eberhardt E., Loew S., McDougall S. & Hungr O. (2009) - *Hazard assessment and runout analysis for an unstable rock slope above an industrial site in the Riviera valley, Switzerland*. Landslides, **6**(2): 111-119.

