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DEBRIS FLOW MITIGATION AND CONTROL IN THE DOLOMITES (NORTH-EASTERN ITALY)

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EXTENDED ABSTRACT

I pericoli idrogeologici nella zona di Cortina d'Ampezzo (Dolomiti Orientali, Italia), rappresentati da frane e colate detritiche (*debris flow*), sono riconosciuti e studiati da tempo. I *debris flow*, in particolare, provocano spesso vittime e notevoli danni economici, a causa della loro elevata velocità, dei grandi volumi di detrito trasportati e della loro frequenza.

Un *debris flow* con frequenza annuale, del tipo *hill-slope*, minaccia l'area urbanizzata di Fiames e la S.S. 51 di Alemagna; nel settembre 1997 si è verificato un evento che ha trasportato 25.000 m^3 di detriti, sbarrando temporaneamente il corso del T. Boite.

Il bacino roccioso è formato da dolomia massiccia e calcari del Triassico superiore e Giurassico inferiore, che rappresentano la sorgente di detrito; il canale di flusso principale è inciso nel detrito di falda eterogeneo; l'area di deposito non confinata ha pendenze tra 5° e 10°.

Dopo l'evento del settembre 1997, è stato costruito un bacino di deposito dei sedimenti, a protezione della strada statale S.S. 51 e dell'area di produzione artigianale, e per impedire lo sbarramento del Torrente Boite. Il bacino è stato costruito realizzando un rilevato lungo circa 200 m ed alto 4 m trasversalmente alla direzione del canale di flusso principale. A causa di vincoli topografici, la forma della vasca, avente una capacità di soli 15.000 m^3, era molto stretta e non si è rivelata idonea a contenere il materiale di colate successive.

Nel 2002 è stato installato un sistema di allarme per arrestare il traffico sulla S.S. 51 in caso di *debris flow*, basato sia sulla rilevazione precoce delle vibrazioni del terreno indotte dal *debris flow* che sul superamento di una soglia di spessore dei sedimenti nel bacino di contenimento.

Negli anni successivi, è stato condotto uno studio accurato del sito per la progettazione di opere per la mitigazione del rischio da *debris flow*, che include: il calcolo del volume di progetto del *debris flow*; la determinazione delle reali proprietà geotecniche dei materiali; la modellazione numerica dei flussi di detriti, al fine di valutare la forza di impatto della colata di progetto che agisce su una struttura di mitigazione.

Gli effetti di una colata di progetto sono stati simulati utilizzando il programma FLO-2D, creando una mappa del rischio, e quindi calcolando la pressione di impatto P_i (Pa) prodotta su una struttura di mitigazione disposta perpendicolarmente alla direzione del flusso. Il valore calcolato è stato adottato come pressione di impatto di progetto nell'area di deposizione.

I criteri generali adottati per la progettazione delle opere di controllo e mitigazione del rischio possono essere così riassunti: costruzione di strutture relativamente a basso costo, attraverso l'ottimizzazione della topografia del sito e l'uso di materiali locali; minimizzazione del rischio per gli utenti della S.S. 51 e per le strutture a valle della stessa; riduzione al minimo dei quantitativi di materiale grossolano depositato nel bacino di raccolta.

Nell'area sorgente della colata detritica di Fiames non sono possibili interventi di riduzione del rischio potenziale; nell'area di deposizione, le opere di mitigazione consistono in un argine terminale; un bacino di contenimento immediatamente a monte dell'argine, per contenere i detriti all'interno dell'area di deposizione alla base del versante, dotato di strada di servizio per la manutenzione del bacino dopo un evento; una barriera e una serie di schermi filtranti da disporre sul lungo il percorso di flusso principale e nell'area di deposizione, per disperdere il flusso detritico, per contenere parte del materiale trasportato e per sostenere la forza di impatto, e per controllare la velocità.

Nell'area di deposizione non confinata e nel canale principale, a monte dell'argine terminale, è prevista l'installazione di schermi filtranti allo scopo di rallentare il flusso detritico, di separare la frazione più grossolana dall'acqua e dalla frazione fine e quindi per favorire la deposizione.

Se gli interventi in quest'area sono impraticabili, come nel sito di Fiames, dopo dettagliati studi geotecnici del bacino di drenaggio, la procedura dovrebbe essere quella di controllare il percorso di flusso e ridurre la velocità nel canale principale e di realizzare il contenimento del materiale trasportato in un'area di deposizione predeterminata. I dispositivi proposti richiedono manutenzione, cioè il detrito depositato all'interno del bacino di raccolta deve essere rimosso dopo ogni evento e devono essere valutati criticamente in modo che la loro efficacia non vada perduta nel tempo.

ABSTRACT

An active debris flow seriously threatens the urbanized area of Fiames, near Cortina d'Ampezzo (Dolomites, Italy) and the National road. In September 1997, following a 25,000 m^3 magnitude debris flow that temporarily dammed the river, a retention basin with a storage capacity of about 15,000 m^3, was built upstream the National road. In 2002 a warning system was installed, based on the early detecting of debris-flow-induced ground vibrations and the overcoming of a flow-stage threshold in the debris basin, linked to a traffic light in order to stop the traffic on the National road in the event of a debris flow. In the following years, after more accurated studies, more effective mitigation measures were designed. The most suitable action to reduce the risk is to control the debris deposition, because the geomorphology of the site does not allow risk mitigation measures along the flow paths. For the design of the mitigation works, the two-dimensional flow routing model FLO-2D has been used to get fundamental information such as possible runout distances, depth, velocities and impact force of the design debris flow. The magnitude of the design debris flow, based on geomorphological and historical data, has been estimated in 30,000 m^3. A debris basin and debris flow barriers and breakers have been considered the most suitable mitigation measures to protect human settlements, infrastructure and supply lines from rain-induced disasters by dissipating the energy of debris flow (floods), filtering coarse solid components and deflecting the flows from the areas at risk.

Keywords: debris-flow hazard, mitigating measures, FLO-2D, Dolomites

INTRODUCTION

Hydrogeological hazards, in the Cortina d'Ampezzo area (Eastern Dolomites, Italy; Fig. 1), mostly posed by large-scale landslides and debris flows, have been recognized for quite some time (Panizza *et alii*, 1996; Genevois *et alii*, 2003). Debris flows, in particular, are a severe natural hazard in this mountainous region, killing people and causing remarkable property damage, due to their high velocity, large volumes and frequent recurrence (Genevois & Tecca, 2016).

Large debris flows seriously threaten a developed area and a National road at Fiames site on the western slope of the Mt. Pomagagnon, along the left side of the Boite River valley. The site, which is within an area of touristic relevance, is affected by a hill-slope debris flow that often varies its flow path from event to event; damming and overflowing in the middle and lower channel, it often causes avulsion. Debris deposition at the slope toe often results in blockage of the main road, houses damage and even damming the Boite River.

On September 5, 1997 a debris flow occurred and temporarily dammed the Boite River. The event was triggered by an intense rainstorm recorded by a rain gauge located 1 km far north, at an elevation of 1325 m. The event initiated at the onset of the main channel. At an elevation of 1500 m, where the slope angle decreases to 20°-23°, from the main channel some secondary channels originated. Further downslope, where the slope angle decreases to 12°-14°, the lateral deposition becomes more and more evident while the main channel proceeds straight through the wood down to the National Road and the Boite River. The total volume of the transported material was estimated in 25000 m^3. About 52% of the total volume deposited on the slope below 1500 m a.s.l. with depths of 0.8-1.1 m, whilst the rest flowed further downslope to the Boite Torrent.

Before 1997 the engineering geologic characterisation of the site essentially underestimated the debris flow processes, leaving structures unprotected. In fact, human activities had been developed at the toe of the hill slope susceptible to debris flow occurrence.

Since that event, recognition, evaluation and mitigation of the debris flow hazard have been a principal concern of local and state Agencies as well as of Earth Science and Engineering Research at various Universities. After the 1997 debris flow event, a concentrated effort has led to a confident approach to implementing debris flow mitigation measures for the Fiames site.

Fig. 1 - Aerial view of the Cortina d'Ampezzo area and Fiames site. Image Google Earth 2017

This paper describes the general geologic engineering considerations that are the basis for the design of debris flow hazard mitigation measures on the Fiames slope. We describe parameters and illustrate a representative plan of mitigation devices suitable for the specificity of the site.

DESIGN CONSIDERATIONS

Engineering geology

Engineering geologic site characterization is the most important factor in designing and positioning effective debris flow mitigation devices. This characterization, together with the hydrological characteristics of the site, allows a determination of whether a slope has a potential for failure, whether the hazard can be mitigated, and where a proposed mitigation device would be more effectively positioned. Based on the experience gained locally in Cortina d'Ampezzo area from a number of debris flow events in the late '90, a debris flow can occur on virtually any loose debris deposit subjected to a minimum of 25 mm of total rainfall, in the form of a short, intense precipitation (e.g. 60 mm/hr over a 10 min period; Tecca *et alii*, 2003). This is regardless of slope aspect and underlying lithology, provided that runoff is concentrated and the slope gradient of the source area is above 30° (Tecca *et alii*, 2003). Genevois *et alii* (2000), Deganutti *et alii* (2003) and Gregoretti & Dalla Fontana (2008), among others, have worked extensively with debris flow processes in the Cortina d'Ampezzo area and have delineated additional hydrologic and geologic factors that contribute to debris flow initiation. The initial failure typically involves the channel bed material and the flowing mass progressively increases its volume along the initial part of the channel, by bed entrainment (Berti *et alii*, 1999). Erosion and entrainment of material produce a scour rate of 5-15 m^3/m for this site (Tecca *et alii*, 2006).

We observed that the most common site for debris flow initiation is at the outlet of the rock basin (Tecca & Genevois, 2009), although other geomorphic sites experienced failure. Examples include oversteepened colluvial slopes and debris deposits along channel beds. In all cases, however, concentrated runoff is primary factor of initiation (Dietrich *et alii*, 1986; Genevois *et alii*, 2000). The water-flow from contributing areas concentrates in gullies and fractures, then seeps into the debris producing shallow slope failures, which can almost immediately liquefy and flow down the slope.

Following Marchi & Tecca (1996), we describe the three distinct geomorphological units involved in a debris flow process: rock basin and source area; main flow track; and depositional area (Fig. 2).

Rock basin and source area

The upper rock basin is formed of Upper Triassic to Lower Jurassic massive dolomite and limestones, that are the source of coarse debris and boulders. The source area of the debris flow is located between 2178 and 1820 m a.s.l.. Debris consists mainly of gravel and coarser elements (> 10 cm), with boulders up to 3-4 m occasionally present.

Main flow channel

Rock debris accumulates in the very upper channel forming a thick talus on the slope from the base of the rock cliffs to the valley bottom (1268 m a.s.l.); it consists of poorly sorted debris containing boulders up to 3-4 m in diameter and includes heterogeneous scree, alluvium and old debris flow deposits. Three major channels and some minor ones originate from the same source area and are related to different events. The main channel is incised into the talus, with depths ranging from 3 m to 6 m, widths from 10 m to 22 m and length of 1500 m, with slope between 27° (upper channel) to 13° (lower channel). In these channels, the debris flows down scouring and entraining additional material. The main morphometric parameters of

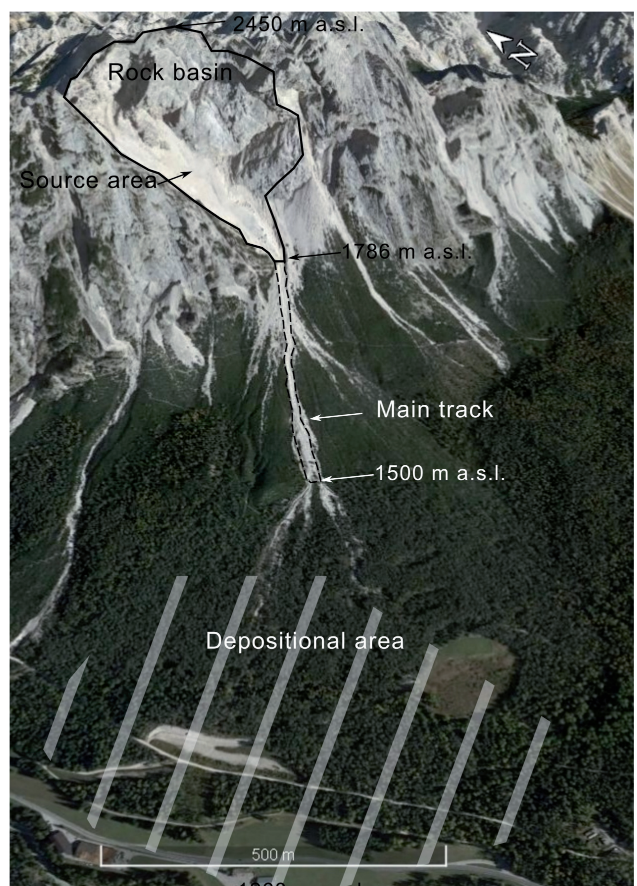

Fig. 2 - South-westerly view of drainage basin in Fiames, Cortina d'Ampezzo area, displaying geomorphological units of debris flow: rock basin and source area, main track, and depositional area. Image Google Earth 2017

Rock basin area (km^2)	0.19
Basin maximum elevation (m a.s.l.)	2450
Rock basin outlet elevation (m a.s.l.)	1786
Source area mean slope (°)	40
Main flow channel length (m)	440
Main channel depth (m)	3-8
Main channel width (m)	10-22
Mean main channel slope (°)	20
Apex of deposition area elevation (m a.s.l.)	1500
Valley bottom elevation (m a.s.l.)	1268
Deposition area mean slope (°)	10

Tab. 1 - Main morphometric parameters of Fiames site

Fiames site are listed in Table 1.

Depositional area

The unconfined depositional area (Fig. 2) extends between altitudes 1500 and 1265 m a.s.l., with gradient varying between 5° and 10°. Historical records on debris flows at Fiames exist back to the 19th century. Most recent flows, from 1992 to 2013, had volumes ranging from 8,000 m^3 to 25,000 m^3. The depositional area has been substantially modified by interventions for the restoration of traffic and safety, implemented following the debris flow events of September 1997 and July 1998.

Geotechnical engineering

Until 2005 the design of debris flow mitigation measures at the Fiames site was based principally on an empirical approach. Following the September 1997 event, a storage basin was built to protect the National road S.S. 51 and the craft production area located just below the main road, and to prevent the possible damming of the Boite Torrent (Fig. 3). The storage basin confining dike, built at an altitude of 1320 m a.s.l. using the same debris flow material, and oriented at right angle to the main flow channel, was about 220 m long and 4 m high (dike A in Figure 3). At the northern end of the basin, a shorter dike, approximately 40 m long (dike B in Figure 3), was built, in order to extent the protected section of the road S.S. 51.

The lower end of the storage basin is provided with a rock filter made of boulders (Fig. 4); it drains the debris flow matrix (water and fines) from depositing material through a large culvert pipe, under the roadway, up to the Boite Torrent.

In conjunction with this form of control, a berm impediment immediately upstream the basin was constructed, made of natural debris, with a holding function for minor events (Fig. 5).

Due to topographical constraints, the shape of the storage basin was very narrow (maximum bottom width about 20 m) and proved itself unsuitable to distribute evenly the flowing material, for its high viscosity, in the whole basin, as it tends tends to

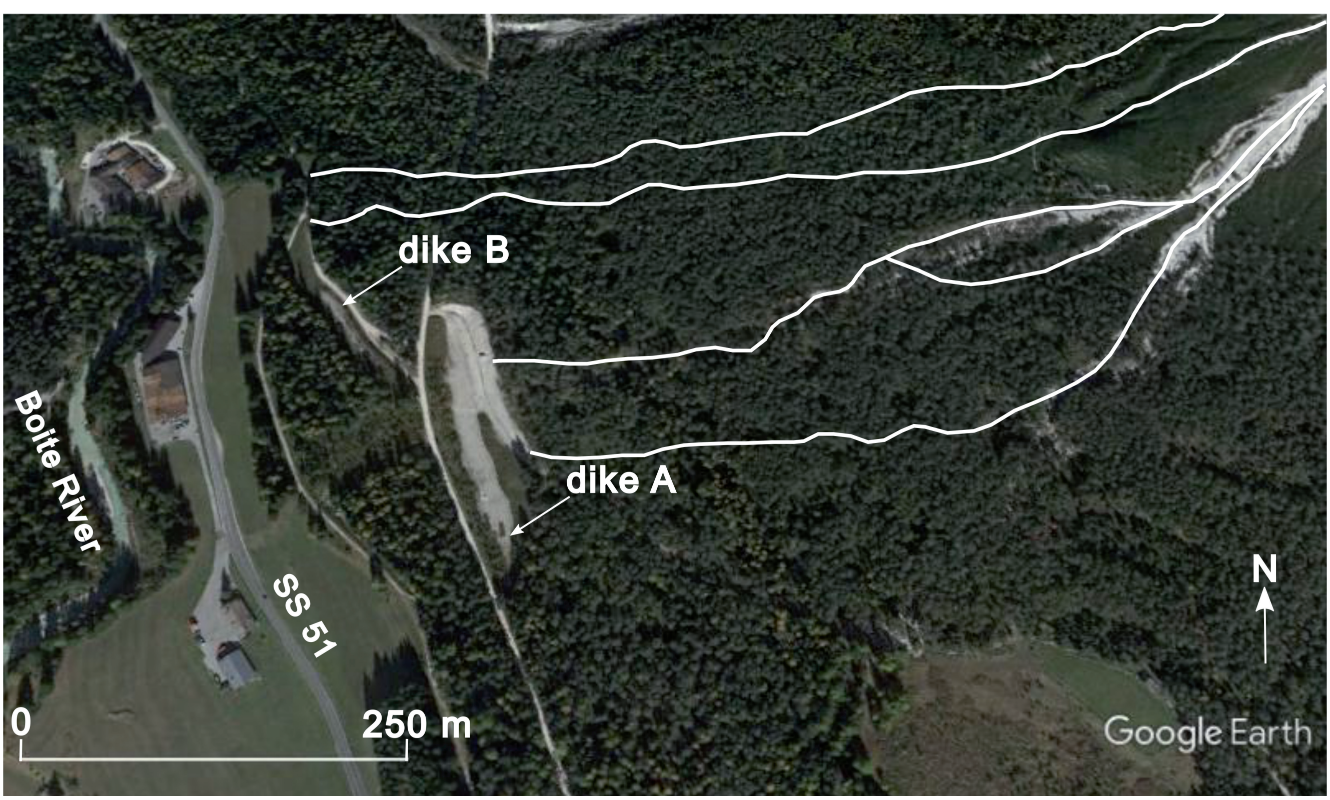

Fig. 3 - BImage of the retention basin and dikes of 1997 and position of the debris flow paths (in white). Image Google Earth 2017

Fig. 4 - North-westerly view of dike A

Cohesive strength (Pa)	0
Effective internal friction angle (°)	38-42
Void ratio	0.33-0.36
Saturated density (kg/m^3)	1960-2160
D_{60}/D_{30} ratio	3.9-14.3

Tab. 2 - Debris flow mixtures properties

deposit mainly along the flow direction, rather than to spread laterally, as in the low viscosity fluids.

In spite of the fact that the 1997 debris flow had a total volume of 25,000 m^3, the storage basin was built with a capacity of only 15,000 m^3, so it was not effective to contain subsequent flows.

In 2002 a warning system was installed in the debris basin area, based on the early detecting of the debris flow-induced ground vibrations and the overcoming of a flow stage threshold. The detecting sensors were linked to a traffic light in order to stop the traffic on the road S.S. 51 on the occurrence of a debris flow. The system consists of two flow-level measuring stations (ecometers), installed on the basin embankment, of an acoustic sensor (3D geophone) buried in the right levee of the main flow channel, and by two traffic lights along the S.S. 51 itself.

In the following years a more accurated study of the actual geotechnical properties of the debris material has been carried out with numerical modelling of debris flows, to evaluate the pressure exerted by the flow on a mitigation structure.

The natural dry bulk density, evaluated though on-site replacements tests ranges from 1,960 to 2,160 kg/m^3 (Marchi & Tecca, 1996); similar values were obtained by Iverson (1997).

Debris flow material has been sampled along the flow channels and in the deposition area, the main geotechnical properties of the fraction < 2 mm are reported in Table 2.

The FLO-2D program was used, after a proper calibration of the model on the September 1997 event, to simulate a design debris flow as much as 30,000 m^3, creating a hazard maps first, based on a methodology developed by Garcia *et alii* (2003, 2004). The process intensities are defined in terms of a combination of flow depth h and the product of h and velocity, in each grid element, outlining the areas characterized by 3 hazard levels, from low to high.

FLO-2D calculates the pressure P (Pa), induced by the impact of the debris flow with the barrier in dynamic conditions, from the application of the momentum balance (treated as a homogeneous fluid), as follows:

Fig. 5 - Rock debris berm in the transport/depositional area

$$P = \rho_m v^2 \quad (1)$$

where ρ_m is the mean density (kg/m^3) of the impacting fluid and v is the velocity of this fluid (m/s).

The impact pressure P_i is reported by FLO-2D as a force per unit length (P x flow depth); the user can then multiply the P_i (N/m) by the structure length within the grid element, to get a maximum impact force on the barrier (FLO-2D, 2006).

The modulus of the impacting force F_i (N) is computed by the momentum equation:

$$F_i = \rho_m v^2 A \sin \beta \quad (2)$$

where A is the impact surface of the grid element of the barrier (flow depth h x structure unit length l) in m^2, and β is the angle between the barrier and the flow direction in deg, in order to evaluate the effective force component normal to the barrier itself.

Hungr *et alii* (1984) proposed to multiply the flow depth by 1.5, to account the formation of a stagnant debris wedge in front of the barrier toe:

$$F_i = 1.5 \rho_m v^2 A \sin \beta \quad (3)$$

The impact pressure Pi produced on a structure arranged perpendicular to the flow direction is therefore calculated according to the following expression:

$$P_i = F_i / 1.5 h_{max} = 2/3 \rho v^2 \quad (4)$$

where h_{max} is the maximum flow depth.

The ultimate design impact pressure P_{impact}, for structures positioned at right angles to the debris flow path in the deposition area, has been calculated assuming a debris flow density equal to 2,000 kg/m^3, and a mean velocity value of 5 m/s, as shown by the magnitude of the velocity vectors computed by FLO-2D.

The general purpose of mitigation measures, is to control the velocity and course of descent, and to provide containment at a safe location at the base of the slope.

The preliminary design for debris flow mitigative works is based upon the following criteria: to construct relatively low-cost structures, according to the site topography and through the use of local materials; to minimize the risk to users of the National road; to minimize the amount of coarse-grained sediment that enters the storage basin from future debris flows.

The mitigative structures would be constructed on the lower fan of Fiames, upstream the National road S.S. 51. They would consist of a terminal debris berm; a storage basin

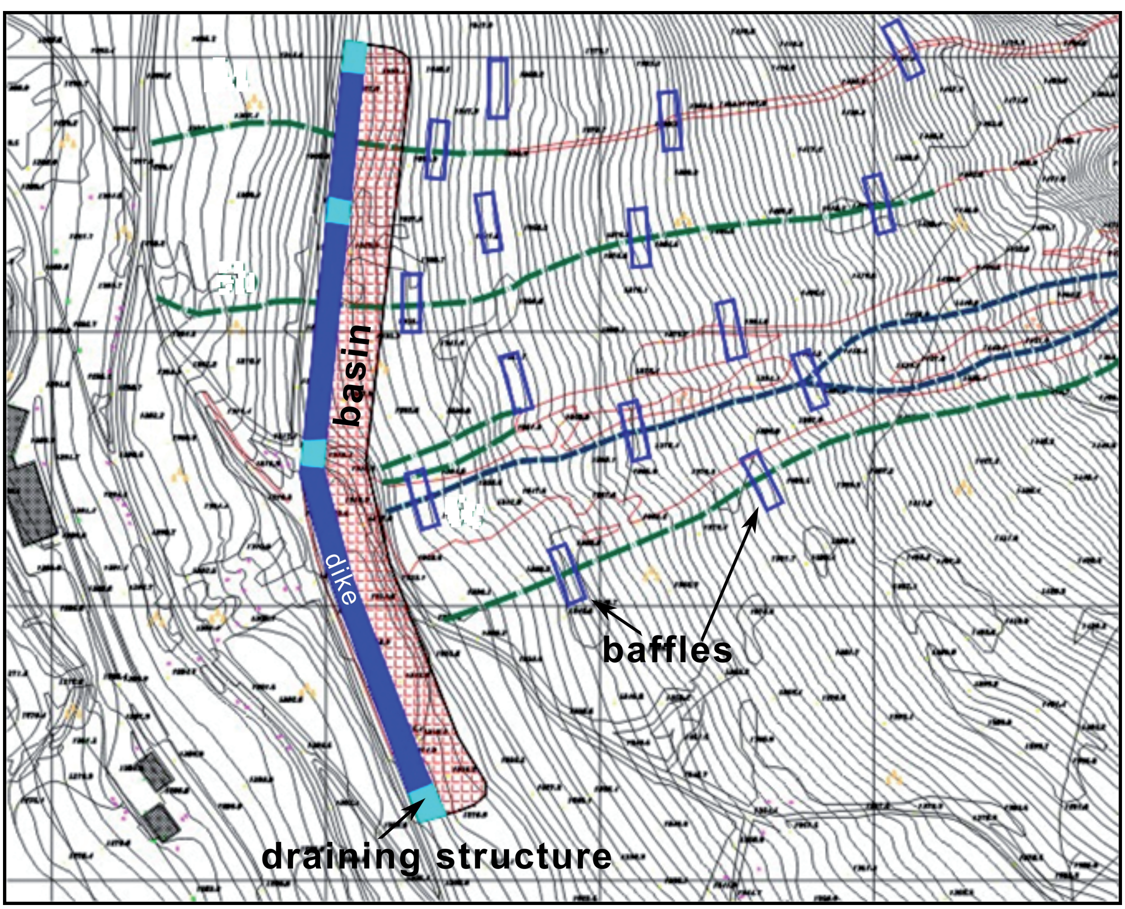

Fig. 6 - Plan of storage basin and impediments to flow (baffles). The topographic grid is 200 m x 200 m

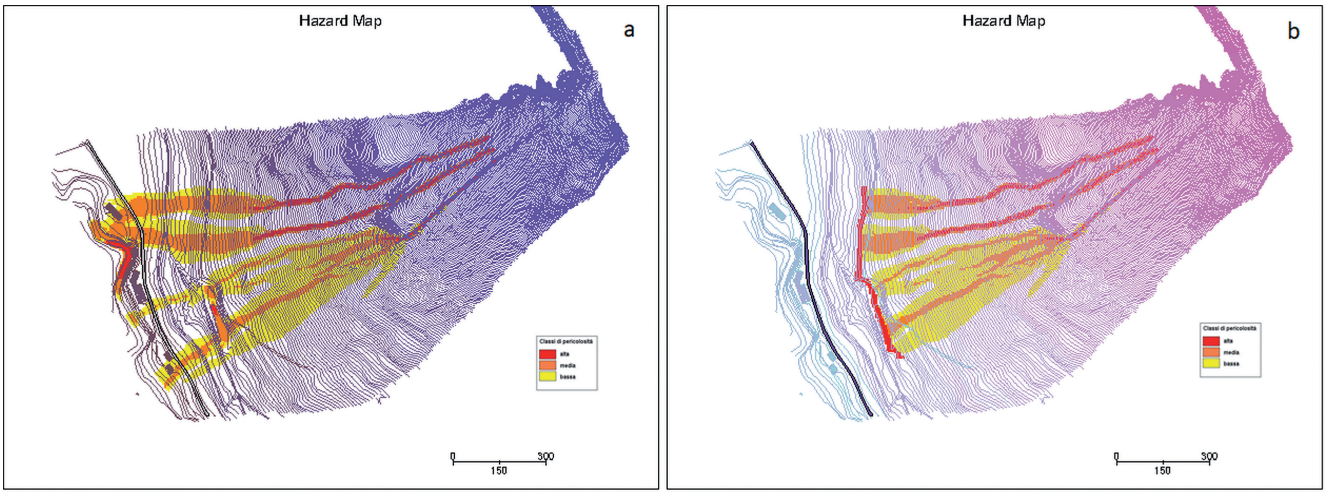

Fig. 7 - Hazard maps from FLO-2D simulations. (a): natural conditions; (b): presence of a terminal berm

upstream the berm to trap the debris within the deposition area at the base of the slope, and a road access for the basin cleaning after an event; a debris barrier and baffles along the main flow path or depositional area to disperse the debris flow, to contain part of the debris and to sustain the full impact force, and to control the velocity.

A general arrangement of these features is shown on Figure 6.

The new embankment is located in continuation of the pre-existing one. In this way both the existing containment structure and the geometry of the depositional area are being optimized. On the basis of the FLO-2D simulations (Fig. 7a and b), the dike, made of the same granular material from the excavation of the basin, would have a total length of 800 m, a minimum height of 4.5 m, and a ridge width of 2.5-3.0 m.

The possibility of creating only unconfined deposition areas (Van Dine, 1996) was excluded for operational and reliability reasons, in addition to the significant landscape impact that it would have, as well as the connected works that involve substantial modifications of the natural flow paths.

Mitigation measures design

The effects of debris flows can be reduced by a number of mitigative methods. The type of debris flow control structure on a debris fan depends on the features of the debris flow, of the fan, the purpose of the mitigation, and the available economic resources, and also on the equipment available for the construction, and maintenance of the structure. Different types of debris flow control structures are sometimes used in conjunction with one another.

In general, debris flow control structures can be divided into two basic types: open (unconfined deposition areas; baffles; check dams; lateral/deflection/terminal walls, berms, or barriers) and closed (debris racks, or some other form of debris-straining structures located in the channel; and debris barriers and storage basins).

Fig. 8 - Aerial view of source area. Image Google Earth 2017

The most appropriate mitigation measures designed for the Fiames site are described below.

Source area

The debris-flow source area of Fiames is very difficult to access and it is not possible to act there for mitigating potential hazards, neither for grading the slope, nor installing riprap or retaining walls, given the very steep gradient and the very high rate of debris production (Fig. 8).

Main channel and depositional area

Baffles. Impediments to flow, or baffles, are used primarily to slow down a debris flow and thereby encourage its deposition, placed often in unconfined areas. In the main or depositional area they are used also to separate the coarse grained debris from the fine-grained debris and water of the debris flow, thus encouraging the coarse-grained portion to be deposited, causing the reduction of the solid concentration of the flow, with a reduction of its viscosity. The baffles can be constructed of earth berms, timber, or steel, and can be emplaced as single units, in lines or staggered. To be effective, the coarse grained debris must be removed from behind the straining structure after every event. The slit aperture is designed at 1.5 to 2 times the maximum mean diameter of the boulders; the openings used for the straining structures associated with debris barriers and storage basins range between 0.5 and 1.00 m. The configuration and number of baffles and their spacing is adapted to the channel characteristics and mitigation requirements, and must be designed with respect to the eventual debris clean-out.

At the Fiames site 15 staggered baffles would be constructed upstream the terminal berm of the storage basin, to increase its functionality and efficiency. The baffles, emplaced within the three main flow channels, would consist of rows of cylindrical steel elements, embedded in a reinforced concrete foundation and designed to sustain the impact forces of individual boulders. The baffles (Fig. 6), would have row lengths of about 20-25 m and heights about 2.0 m.

The openings have been designed also in relation to their position on the slope with respect to the main flow channel. Two baffle rows are emplaced along the main flow channel with openings 1.5 m wide; a baffle row with openings 0.8-0.6 m wide, is emplaced at the outlet of the main channel. The other baffle rows would have smaller openings. A road access to clean out to the structures would be constructed.

Debris barriers and storage basin. These structures are located across the debris flow path and designed to encourage deposition. The debris-straining structure, a debris barrier, must incorporate a weir or spillway into the structure to allow fine-grained sediment and water to escape, while the coarse-grained debris is contained within the storage basin located upslope of the barrier. The area upstream of the debris barrier can be excavated to reduce the gradient and to increase storage capacity. After a debris flow has occurred, the coarse-grained debris trapped behind the debris barrier must be removed. Design considerations include: design magnitude or volume of a debris flow, size and gradation of the coarse-grained debris, potential runout distance, impact forces, and deposition angle.

Terminal berms, or barriers are constructed across the path of a debris flow to cause deposition being a physical obstruction to flow. Once a debris flow has been deposited upstream of a terminal structure, the coarse-grained debris must be removed from the area. Terminal walls, berms, or barriers are usually located as far as possible downstream from the apex of the fan to get a larger area for deposition, and to minimize the impact forces and run-up on structures. The artificial deepening of the deposition area lowers the gradient, increases storage capacity, and decreases runout distances, impact forces, and run-up.

DISCUSSION AND CONCLUSION

We are now aware that many mountain slopes subjected to even short intense rainfall, pose a potential hazard by debris flow to human activities and structures located downslope. Construction in these areas is therefore severely limited by this potential hazard. When evaluating the foundation conditions for debris flow mitigation works on a particular mountain site, especially if positioned at the base of the slope, it is now becoming a standard to assess both the potential for debris flow initiation for the drainage basin and hillside engineering morphologic conditions. We now realize that the essence of debris flow mitigation is to recognize the potential hazard at source area level. If this is deemed impractical as in Fiames site, after detailed geotechnical studies of the drainage basin, the procedure should be to control the course and reduce the velocity of a debris flow within the main channel, and to provide containment in a predetermined design deposition area.

We have defined a suite of basic mitigation measures that should be designed and constructed for the Fiames site to reduce the local hazard, although there are many more possible configurations that might be implemented to protect roads and buildings from the ravages of debris flow hazard.

The devices proposed do require maintenance and should be critically evaluated so that their effectiveness would not be lost with time.

In particular after an event, weak elements in the mitigation concept or safety system can be identified and additional measures can be planned accordingly (Hübl *et alii*, 2005).

The application of the numerical code FLO-2D improves the capability to predict debris flow behaviour estimating depths and velocities, identify areas of inundation delineating hazard maps and zone restrictions. The calibration of the model based on data from a (or more) documented debris flow event is a crucial aspect for the accuracy of the simulations in order to choose the most reliable rheological parameters to be used in the simulations of a design event. The simulation of the September 5, 1997 shows that the general flow behaviour is well replicated in terms of extent of the flooded area, runout distance, estimated thickness and velocity, using a viscosity of 1.0 Pa s and a yield stress of 175 Pa, calculated from the back analysis of the event. These parameters have been used to calculate the impact pressure for the design of mitigating measures.

Unfortunately the proposed structures have not been built yet; since no large events happened in the last years, the construction works have been postponed "*sine die*"… probably not before the next disastrous event.

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