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Structural and non-structural mitigation of landslide risk in road connections: the integration of monitoring and early warning devices in the Scascoli Gorges (northern Apennines, Italy)

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The Scascoli Gorges (25 km south of Bologna, Savena River Valley) display an intrinsic structural predisposition to slope instability, due to stratigraphic and tectonic features, resulting in several landslide bodies of different types and sizes. In particular, both the left and the right cliffs of the Gorges have been affected by huge rock falls involving weathered and fractured sandstones. The rock fall events recorded in the last few years are impressive: on October 15th, 2002 a rock volume of about 20.000 cubic meters detached from the left cliff, damming the Savena riverbed and completely destroying 150 meters of the Fondovalle Savena provincial road. On March 12, 2005 a rock slope failure of 30.000 cubic meters occurred, developing as a toppling-rock fall that, again, dammed the river and destroyed the road for a length of about 100 m. Despite the fact that the road represent an important connection from the upper part of the valley to the city, in both cases, no accidents and casualties were recorded.

From 2005 onwards a large civil protection plan was set up in order to design protection and consolidation works, and to manage the risk posed to the road on the elements at risk, both directly and indirectly (people, road, economic activities etc.). Site characterization, in situ monitoring, slope stability analyses and alarm system, in the frame

of residual risk assessment and management after the 2005 event, are here discussed.

After the last major rockfall event and the first emergency response (removal of fallen blocks), two main sources of risk threatened the road in the Scascoli Gorges. One was the risk that single rock blocks resting on unfavourably orientated joints (volume in the order of dm^3 to $10^0 m^3$) would detach from the cliff and impact the road. The other was the risk associated with an overall failure of the rock cliff such occurred in 2002 and 2005 (volume in the order of $10^5 m^3$). In order to reduce the hazard and to drop the risk below an acceptable level, both structural and non-structural mitigation measures were combined.

The first mitigation measure consisted of slope flattening and benching aimed to reduce the driving force in the cliff affected by the 2005 rockfall. Slope was excavated by blasting and heavy ripping to an average slope of approximately 50˚. Slope profiling had the double positive effect of increasing the global safety factor of the rock slope and grading the slope away from the road, thus reducing the hazard related to single rockfalls. Furthermore, a rockfall barrier with an energy absorption capacity of 1000 kJ was installed at mid-slope where the cliff was still too close to the road (10-15 m). Structural measures also included the construction of a earth wall at the toe of the cliff, the protection of river banks against undermining, and the rebuilding of the road subgrade using large rock blocks fastened with concrete and stainless steel nets.

Non-structural mitigation measures consisted of an automated monitoring system and of a cable alarm system. The monitoring system is composed by three electrical crack-meters installed across major discontinuity planes and one thermometer. The data are collected every four hours, stored in the field and retrieved weekly via GSM. The alarm system was installed along the road guard rail and it consists of a cables pair coupled with a current detector. Whether an interruption of the current flow is detected, the system turn on two red traffic signal signs placed at the entrance of the Gorges and send an SMS alarm to nominated mobile phone numbers.

The efficiency of the mitigation measures were evaluated in terms of risk reduction. The level of risk from rockfall was quantified by considering the following hazards: i) impact of a rock on a moving vehicle, ii) impact of a rock on a stationary vehicle; iii) impact of a vehicle on a stationary rock that is obstructing or blocking the road. The overall risk level was computed as sum of the probabilities of single accidents multiplied by the probability of death. By comparing the overall risk before and after the works, we demonstrated that the adopted mitigation measures have successfully decreased the level of risk and that the level of residual risk is well below the values commonly selected for acceptable risk.