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DETAILED REPORT OF ASSISTANT CONTRACTOR CNR IRPI PERUGIA

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Section 6.1 - Background

In the mountain areas of Europe rock falls are a common type of fast moving landslides. Rock falls range in size from cobbles to rock masses thousands of cubic meters in size, and travel at speeds ranging from few to tens of meters per second. Rock falls occur in all climatic regions and are caused by a variety of triggers, including earthquake shaking, freeze-thaw cycles, and rainfall (Broili, 1973; *Varnes*, 1978; *Whalley*, 1984; *Cruden and Varnes*, 1996). In spite of their relatively small size, rock falls are among the most dangerous and destructive mass movements, and pose a severe threat to human, properties and utilities where they occur. In Italy rock falls are one of the primary causes of landslide fatalities (*Guzzetti et al.*, 2000).

Despite the fact that rock falls are common and that they are a relatively simple landslide type to model, only a few attempts have been made to evaluate rock fall hazard, and the associated risk, spatially, i.e., over large areas or along long transportation corridors (*Fenti et al.*, 1979; *Bunce et al.*, 1997; *Hungr et al.*, 1999). In the DAMOCLES project we have designed a new three-dimensional, spatially distributed rock fall simulation software (*Guzzetti et al.*, 2002), we have tested the simulation program at various scales and in different physiographical regions of Europe and in the United States (*Guzzetti et al.*, 2003b), and we have devised methods to ascertain rock fall hazard spatially, based on the outputs of the simulation program (*Crosta and Agliardi*, 2003; *Guzzetti et al.*, 2003a).

Section 6.2 – Scientific/technological and socio-economic objectives

Rock falls occur along natural slopes and artificial cuts. In many mountain areas of Europe rock falls represent the main landslide treat to the transportation network. Despite the frequency and potential destructiveness of these fast moving landslides, little has been done to determine rock fall hazards and the associated risk over large areas, or along long transportation corridors. In general rock falls are investigated only at the local scale, and remedial measures are designed to solve local instability problems. For this purpose several computer programs have been developed to simulate the fall of a boulder down a slope and to compute rock fall trajectories. Two-dimensional simulation programs were presented by *Piteau and Clayton* (1976), *Bassato et al*. (1985), *Falcetta* (1985), *Bozzolo and Pamini* (1986), *Hoek* (1987), *Paronuzzi* (1987), *Pfeiffer and Bowen* (1989), *Pfeiffer et al.* (1991), *Azzoni et al.* (1995), *Stevens* (1998), *Paronuzzi and Artini* (1999), and *Jones et al.* (2000). *Descouedres and Zimmermann* (1987) and *Scioldo* (1991) proposed three-dimensional rock-fall simulation programs. Most of the available software works reasonably well only in small areas, for which detailed thematic information, including topography and the types of materials (soil, debris, rock) cropping out along the slope, is available. The available simulation programs are unsuited to ascertain rock fall hazard over large areas, such as an entire Province, a river basin or a valley extending for tens or hundreds of square kilometres, for which detailed thematic information may not be available. In addition, two-dimensional simulation programs work along pre-defined slope profiles, and do not take into account the three-dimensional effect of topography on rock fall trajectories. This is a limitation along steep channels, where the topography is concave (i.e., a hollow) or convex (i.e., a fan), at the apex of a fan, or in any other area where minor changes in topography influence rock fall trajectories (*Guzzetti et al.,* 2002; *Crosta and Locatelli*, 1999).

One the goals of the DAMOCLES project was the development and testing of GIS-based methods to determine landslide hazards in mountain areas, using field data, available databases and innovative modelling tools. To achieve this goal we have designed and tested a new rock fall simulation program capable of computing three-dimensional rock fall trajectories, and of preparing spatially distributed maps of the kinematics and the frequency of rock falls over large areas, using topographical and thematic information that was readily available or that could be obtained quickly and at low cost. We have also devised a set of methodologies to exploit the outputs of the rock fall simulation program to ascertain rock fall hazards and risk in mountain areas ranging in size from few to several hundreds of square kilometres.

Maps showing the outputs of the rock fall simulation software, and maps of the rock fall hazard and risk obtained from the analysis of the modelling outputs were presented to various end-users, including the Geological Survey of the Lombardy Region, in northern Italy, the Civil Protection office of the Perugia Province, in central Italy, and the National Park Service, in the USA. End users proved to be interested in the results obtained. In the Lombardy Region, using the modelling software we were able to ascertain the (approximate) extent of the territory potentially affected by rock falls in large alpine valleys, e.g., 28.4% in Valcamonica (~1450 km^2) and 22.0% in the Lecco Mountain area (~600 km^2) (*Guzzetti et al*., 2002). This information, previously unavailable, is important for planning landslide defensive strategies at the regional scale. For a limited sector of the Nera River valley, in central Italy, the modelling software allowed determining the section of roads subject to rock fall hazards, and to evaluate the efficacy of the existing rock fall defensive measures. The analysis proved that despite the presence of the extensive defensive structures, residual rock fall risk still exists along the Nera River valley (*Guzzetti et al*., 2003a). This is an important information for the Perugia Province, the organization responsible for the safety and maintenance of the regional roads in the area. A map showing the extent of the area potentially affected by rock falls in the Yosemite Valley (California, USA) obtained using the simulation program was compared with previous rock fall hazard assessments in the same area (*Guzzetti et al*., 2003b) and results were presented to the National Park Service. Whether the NPS will adopt the computer model as an alternative or as integration to the 22° shadow angle line or the talus line (*Wieczorek et al*., 1988, 1999) currently used to identify rock fall hazardous areas is unknown. The empirical approach is simpler than the computer model, and some effort will be needed to transfer the new technology to the NPS (*Guzzetti et al*., 2003b).

Section 6.3 – Applied methodologies, scientific achievements and main deliverables

Working Package 2

We designed, developed and tested a new simulation program that generates simple maps useful to assess rock fall hazards and risk, using GIS technology to manipulate existing thematic information available in digital format. The program STONE simulates in three-dimensions the fall of a boulder along a slope (*Guzzetti et al*., 2002). The program was designed to use thematic data already available for large areas, or that could be obtained from geological, geomorphological and land use maps or through reconnaissance investigations, and to generate spatially distributed information useful to assess rock fall hazard at the regional and local scales.

STONE computes three-dimensional rock fall trajectories and spatially distributed raster maps showing the kinematics (velocity and height) and frequency of rock falls. The software can model three of the four "*states*" that a rock fall can take, namely: the free fall of a boulder along parabolic trajectories, the impact of the boulder with the ground and the subsequent rebound, and the rolling of a boulder along the slope. Sliding is not modelled because it is considered to be a negligible part of the rock fall movement process (*Guzzetti et al*., 2002).

The input data required by STONE are similar to the information required by other rock fall simulation programs (e.g., *Descouedres and Zimmermann*, 1987; *Pfeiffer and Bowen*,1989; *Fornaro et al*., 1990; *Pfeiffer et al*., 1991; *Stevens*, 1998; *Paronuzzi and Artini*, 1999; *Jones et al*., 2000), namely: the location of the detachment areas of rock falls, the number of boulders launched from each detachment area, the starting velocity and the detachment angle of the rock fall, the velocity threshold below which the boulder comes to rest, and the coefficients of dynamic rolling friction angle and of normal and tangential energy restitution used to simulate the loss of energy where the block is rolling and at the impact points. STONE differs from other rock fall simulation computer programs in two ways: Topography is provided by a Digital Elevation Model (DEM), and not as pre-defined slope profiles; and values for the coefficients used for modelling the loss of energy at impact points and for rolling are provided in a spatially distributed (i.e., geographical) form. As a result, the outputs produced by STONE are also spatially distributed.

STONE can simulate the inherent natural variability of rock falls in two ways: by launching a variable number of blocks (from 1 to 1000) from each detachment cell, i.e., simulating a different frequency (or probability) of occurrence of rock falls; and by varying randomly, within pre-defined ranges, the starting horizontal angle, the dynamic rolling friction coefficient, and the normal and tangential energy restitution coefficients. The combination of these two possibilities makes the software very flexible, allowing for simulations of different complexity (*Guzzetti et al*., 2002). STONE uses GIS technology to produce two- and three-dimensional (vector) rock fall trajectory lines and raster maps of the same size and resolution of the input grids. For each grid cell the raster output maps show: a) the cumulative count of rock fall trajectories that passed through the cell, b) the maximum computed velocity, and c) the largest flying height (distance above the ground) computed along all of the rock fall trajectories.

Portraying the areas that can be impacted by falling or rolling blocks, the maps provide a spatial prediction of rock fall hazard. In particular, the map showing the count of rock fall trajectories is a proxy for the probability of occurrence of rock falls. For any given cell the map portrays the chance of being crossed (or hit) by a falling boulder. The maps showing the maximum computed rock fall velocity and the maximum computed flying height provide information on the (maximum) expected intensity of a rock fall, a proxy for the maximum kinetic energy expected at each grid cell. A rock fall flying at high speed well above the ground is potentially more destructive than a boulder of the same size rolling slowly on the ground.

STONE was first tested on simple, two-dimensional slope profiles. Results produced by STONE were compared with the outputs of two rock fall simulation software: CSRP (*Pfeiffer and Bowen*, 1989; *Piteau and Clayton*, 1976; *Jones et al*., 2000) and RocFall (*Stevens*, 1998). Comparison was not straightforward because outputs produced by the three programs were different, and because STONE does not use a predefined slope profile to perform the simulation. Nevertheless, results obtained by STONE were in good agreement with those obtained with the other two programs (*Guzzetti et a*l., 2002). STONE was then tested in simple, but realistic, three-dimensional settings. Such tests proved the importance of simulating rock falls in three-dimensions, particularly in complex topographical settings (e.g., couloirs, channels, debris cones, etc.) (*Guzzetti et a*l., 2002, *Crosta and Locatelli*, 1999).

STONE was then applied in sample areas ranging in size from few hectares to more than 1400 square kilometre, in the Italian Alps, in the Apennines of Central Italy, in the Pyrenees, in Island, and in California. In all the tests results proved to be realistic and in good agreement with local information on rock fall events (*Crosta and Agliardi*, 2003; *Guzzetti et al*., 2002, 2003a, 2003b).

Figure 1 shows two simulations of single rock falls occurred on 16 November 1998 and on 14 September 2001 in the Yosemite National Park, California. The failures reached the Curry Village, located at the foot of a talus slope, or its vicinities, threatening a popular campground present in the area. To perform the simulations, 100 boulders were launched form each source area, consisting of 8-10 cells, each with a ground resolution of 10×10 meters. Hence, between 800 and 1000 rock fall trajectories were computed for each rock fall detachment area. This explains why the extent of the simulated rock fall is larger than the failure mapped in the field, which had probably a smaller volume. There is good agreement between the rock fall deposit mapped in the field (black line) and the simulation computed by STONE. Most of the rock fall trajectories (violet and blue colours) fall within the outline of the rock fall deposit. The yellow area outside the rock fall deposit represents cells where only a limited number of rock falls are expected.

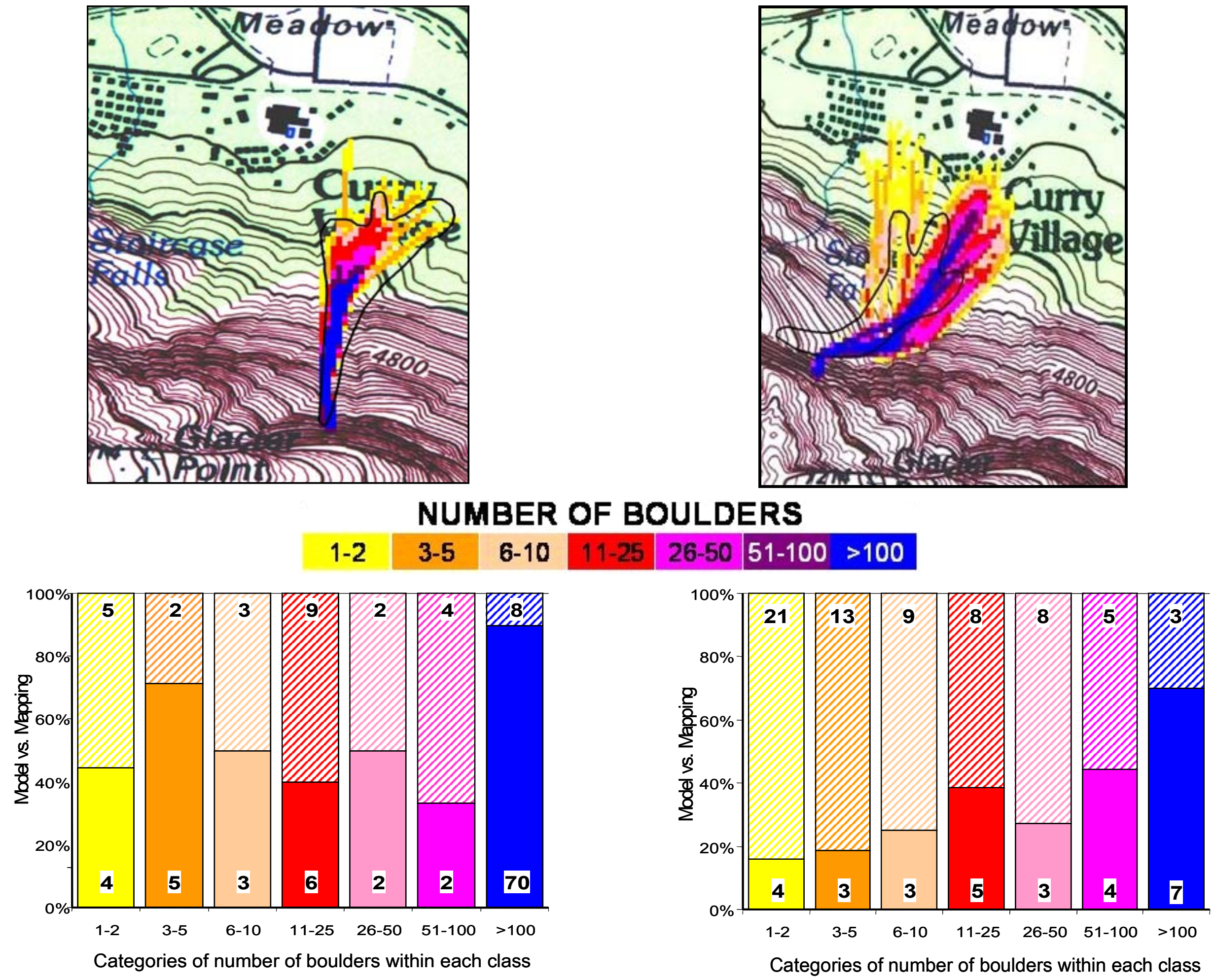

Figure 1. Comparison between mapped landslides (thick black line) and the simulated rock falls (colours) near Curry Village, Yosemite National Park, California. Left: Glacier Point rock fall of November 16, 1998. Right: Ledge Trail rock fall of September 14, 2001. Original scale 1:24,000. Histograms show the number of cells falling inside (solid colour) and outside (oblique pattern) the mapped landslides. Figures in the coloured bars are number of cells. From *Guzzetti et al*. (2003b).

Figure 2 shows three-dimensional views of the rock fall hazard in the eastern section of the Yosemite Valley, California (left) and in the Nera River valley, central Italy (right). The images were obtained by overlaying the maps of the rock falls count on three-dimensional scenes prepared using the available DEMs. Colours show different rock fall counts. Figures 2 clearly shows the local concentration of rock fall trajectories along steep channels and the lateral spreading of rock fall trajectories on talus slopes and debris cones.

As a final test we used STONE to evaluate rock fall risk along the transportation network in an area of about 48 km^2 near the village of Triponzo, in the Nera River valley of central Italy (*Guzzetti et al*., 2003a). In this area rock falls are frequent, and extensive defensive structures, including slope revetment nets, elastic rock fences, concrete walls and artificial tunnels, have been installed to protect the villages and the roads from the rock falls (*Guzzetti et al*., 2003a). Using STONE we determined that about 7.00 km^2 (i.e., 14.58% of the study area) can be affected by rock falls, including 2.05 km^2 of rock fall detachment areas.

Correcting for the steep topographic gradient, the area affected by rock falls extends for about 9.51 km^2. Intersection in a GIS of the maps prepared using STONE with a map of the road network revealed that of the 31.76 kilometres of paved roads in the study area, 9.05 km (28.49%) are potentially subject to rock fall hazard.

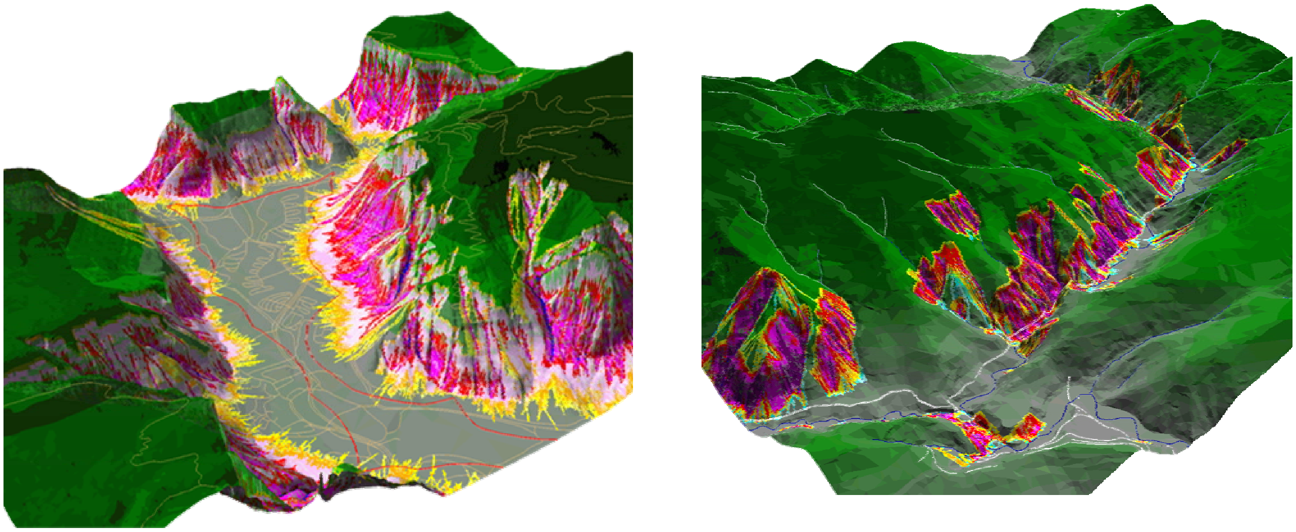

Figure 2. Three dimensional view of the rock fall hazard in the Yosemite National Park (left) and in the Triponzo study area, Nera River valley, Central Italy (right). Colours show rock fall count, from few light blue and yellow, to many and very many (blue and dark violet). From: *Guzzetti et al*. (2003b, 2003a).

To ascertain rock fall hazard in the Triponzo study area we adopted a heuristic approach that assumes that rock fall hazard, H_{rf}, is a combination of rock fall count (*c*), maximum rock fall flying height (*h*), and maximum rock fall velocity (*v*), or $H_{rf} = f\ (c,\ h,\ v)$. Levels of rock fall hazard are attributed using a three-digit positional index, similar to that proposed by *Cardinali et al.* (2002) for other landslide types. In the index, the left digit refers to the rock fall count (*c*), the central digit to the rock fall flying height (*h*), and the right digit to the rock fall velocity (*v*). The index expresses rock fall hazard by keeping the three components of the hazard distinct from one another. This facilitates hazard zoning by allowing to understand whether the rock fall hazard is due to a large number of expected rock falls (i.e., high frequency), a large intensity (i.e., high flying height or high velocity), or some combination of the three. Rock fall hazard is not distributed uniformly in the study area. About 3.39 km^2 of the study area (in plan view) are subject to low (25.49%) or very low (23.01%) rock fall hazard, 1.55 km^2 (22.19%) are subject to intermediate hazard conditions, and 2.05 km^2 are subject to high (15.34%) or very high (13.97%) hazard (*Guzzetti et al*., 2003a).

These estimates do not consider the numerous rock fall defensive structures present in the study area. We performed an inventory of these structures, and we used this information to evaluate the effectiveness of the existing defensive measures in mitigating rock fall risk. This was accomplished in three steps. We first considered the presence of the passive revetment nets. A total of 0.32 km^2 of revetment nets were mapped, mostly along or in the vicinity of the roads. Assuming that the revetment nets were fully capable of preventing rock falls, the area potentially affected by rock falls decreases to 6.49 km^2 (13.51%) and the length of roads subject to rock fall hazard decreases to 6.53 km (20.54%). We then prepared a third rock fall model considering the presence of the revetment nets, the location of the elastic rock fall fences and concrete barriers, and the presence of the artificial tunnels. The model showed that due to the presence of the defensive structures the extent of the area subject to rock fall hazard reduces to 6.27 km^2 (13.07%) and the total length of roads subject to rock fall hazard reduces to 2.92 km, 9.21% of the road network. The combined effect of all the existing defensive structures reduces by about 10.37% the extent of the area subject to rock falls, and by about 67.75% the total length of roads subject to rock fall hazard.

We then attempted to evaluate the efficacy of the existing rock fall retaining structures. This was accomplished in two steps. First, the maximum height of the computed rock fall trajectories was compared to the height of the retaining structures, then the possibility that a boulder could have enough kinetic energy to brake through an elastic fence was considered. The analysis revealed that 20.96% of the rock fall elastic fences or concrete walls could be either bypassed by high flying rock falls, or could be damaged or destroyed by fast moving boulders. To estimate the residual rock fall risk along the roads in the Triponzo study area we prepared a final hazard model not considering the presence of the potentially "*ineffective*" defensive structures. The model revealed that 4.06 km of roads in the study area (12.78%) are potentially subject to rock fall hazard, indicating that despite the considerable reduction in the risk of rock falls due to the presence of extensive defensive structures, residual risk still exists along the main roads in the Nera River valley (*Guzzetti et al*., 2003a).

Working Package 5

Activities conducted by CNR IRPI on WP5 focused on two tasks: a) the design, implementation and maintenance of the DAMOCLES web site (http://damocles.irpi.cnr.it), and b) a test of innovative GIS-based web technology to distribute through the Internet thematic, landslide inventory, and landslide hazards maps in digital form.

The DAMOCLES web site was established on the Internet a few weeks after the project kick off, on May 2001. Since then the web site has been continuously updated whenever new information, documents or other products were made available by the project partners. The DAMOCLES home page (Figure 3) provides access to: a) a description of the project, including the goals of the project, the expected results, the consortium and the project meeting reports; b) a description of the three project study areas, including morphology, geology, and landslide types, and c) the various project deliverables, including thematic, annual and interim reports.

In the recent years GIS-based web technology has improved substantially and has been made available at reasonably low costs. As a results many attempts have been made to exploit the potential of the new technology to publish geographical information (i.e., maps) on the web. The technology allows interested users to find and browse through digital maps directly on the web, using standard Internet applications (e.g., Nestcape©, Internet Explorer©, Opera©, etc.). The users can also customize the way the geographical information is portrayed, and they can perform simple geographical queries, in addition to traditional text based queries. The technology is designed to facilitate the dissemination and use of geographical information amongst very large communities.

Figure 3. The home page of the DAMOCLES project web site. URL is http://damocles.irpi.cnr.it.

In the DAMOCLES project we have made an attempt to apply GIS-based web technology to disseminate the project results, and in particular to publish on the Internet the landslide inventory maps, the landslide hazard maps, and the other thematic maps prepared by the project partners.

The software selected for the experiment was ESRI® Arc Internet Map Server, or ArcIMS™. Various releases of the software were used (i.e., 3.0, 3.1 and 4.0), and the system was updated whenever new versions of the GIS web server became available. The software was originally installed on a personal computer running Microsoft Windows NT©, and was successively moved to a personal computer running RedHat® Linux 7.2 (with release 4.0 of ArcIMS™). The latter solution proved to be more reliable and stable than those based on the Windows operating systems (i.e., Windows NT or Windows 2000). In addition to the ArcIMS™ GIS software, the system uses the Apache web server release 1.3.22-6 and Jakarta-Tomcat release 3.1.1.

The functionalities and capabilities of the system were tested using landslide inventory and landslide hazard maps, and other thematic maps (including topographic, geological and land use maps) provided by the University of Milano Bicocca for the Pioverna river basin, one of the DAMOCLES study areas in the Lombardy Region of northern Italy. Development of the GIS-based web site proved cumbersome, but demonstrated that a significant amount of geographical information showing landslides and landslide hazards can be delivered to interested parties, including concerned citizens, using innovative web-based technologies.

Section 6.4 – Conclusions

Assessing rock fall hazard is a difficult, intrinsically uncertain operation particularly over large areas where the variability of the lithological, morphological and topographical factors controlling the rock fall process is large. We designed, developed and tested a computer program for the three-dimensional simulation of rock falls that proved to be consistent with other two-dimensional rock fall simulation programs, to be reliable in modelling rock falls in three-dimensional morphological settings, and to be capable of providing useful information for the assessment of rock fall hazards and the associated risk (*Guzzetti et al*., 2002).

STONE is a physically-based, three-dimensional rock fall simulation program that computes rock fall trajectories based on spatially distributed, thematic information provided in raster form. The simulation software uses GIS technology to produce two- and three-dimensional rock fall trajectory lines and raster maps showing the kinematics (i.e., velocity and height) and frequency of rock falls. For each grid cell the output raster maps portray: the cumulative count of rock fall trajectories that passed through the cell, the maximum computed velocity, and the largest flying height (distance above the ground) computed along all of the rock fall trajectories. This spatially distributed information can be used to: determine the extent of the rock fall problem in the study area; evaluate rock fall hazards; and ascertain quantitatively rock fall risk. STONE was tested using both natural and synthetic topographic settings. The simulation software was tested in a variety of different topographical, morphological, and geological settings, in Europe and in the USA. The study areas covered a large range of scales, from few hectares to 1400 square kilometres. Results proved to be consistent with the available information on rock falls and rock fall hazard, at the local and the regional scales.

To ascertain rock fall hazard we devised a set of heuristic approaches that assume that rock fall hazard is a combination of rock fall count, maximum rock fall flying height, and maximum rock fall velocity. An approach that proved to be particularly effective to portray rock fall hazard attributes levels of rock fall hazard using a three-digit positional index, similar to that proposed by *Cardinali et al*. (2002) for other landslide types. The index expresses rock fall hazard by keeping the three components of the hazard distinct, facilitating hazard zoning by allowing to understand whether the rock fall hazard is due to a large number of expected rock falls or to a large rock fall intensity. Rock fall hazard maps prepared by analysing the STONE outputs were successfully used to determine the extent of the rock fall problem in large alpine valleys, to determine the section and the length of the roads subject to rock fall hazards, to evaluate the efficacy of existing rock fall defensive measures in mitigating rock fall risk, and to determine residual rock fall risk along the road network.

We think that the results obtained in the areas investigated by the DAMOCLES project are applicable in other mountain areas worldwide, and that the maps produced by STONE can prove useful in ascertaining rock fall hazards and risk in the mountain areas of Europe.

Section 6.5 – Dissemination and exploitation of the results

One of the goals of the DAMOCLES project was to transfer the results obtained, including maps, and new methodologies for landslide hazards and risk assessment, to the local end-users, the scientific community, and the interested citizens. This objective was addressed by a specific working package, WP5, lead by the Project Coordinator. Within WP5, two tasks were accomplished by CNR IRPI, namely: a) the design, implementation and maintenance of the DAMOCLES web site (http://damocles.irpi.cnr.it) and, b) a test of the possibility of using innovative GIS-based web technology to distribute through the Internet thematic, landslide inventory, and landslide hazards maps. The CNR IRPI was also involved in the presentation and discussion of the rock fall simulation program STONE to different end-users.

The DAMOCLES web site was established shortly after the beginning of the project, and has since been continuously updated with new information, data, reports and documents. The World Wide Web proved to be a valuable, easy to use, and efficient way of distributing information amongst the partners, and to disseminate the project results and deliverables to a very large audience using the Internet. An attempt was made to use innovative GIS-based web technology to publish on the Internet landslide inventory and hazard maps, produced by the project partners. Development of the GIS-based part of the DAMOCLES web site was not straightforward, but proved that digital maps showing landslides and landslide hazards can be delivered to interested users, including concerned citizens, using GIS-based web technologies.

Rock fall hazard and risk assessment obtained from the outputs of the simulation software STONE were presented to various end-users, including the Geological Survey of the Lombardy Region, the Civil Protection office of the Perugia Province, and the United States National Park Service. All the end users proved interested in the results obtained. The Geological Survey of the Lombardy Region is using the project outcomes to design new policies for mitigating geo-hydrological hazards at the regional scale. The Civil Protection office of the Perugia Province is considering using the modelling results to identify the areas where rock fall risk is high in the Nera River valley, despite the presence of extensive defensive structures. The U.S. National Park Service might consider adopting the hazard assessment for the Yosemite Valley obtained form the computer model as an alternative to, or in combination with the existing rock fall hazard maps.

Concerning the dissemination and the exploitation of the project results, the DAMOCLES project is to be considered successfully completed.

Section 6.6 – Main literature produced

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