Contribution of Geomatics Engineering and VGI Within the Landslide Risk Assessment Procedures

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Abstract. This paper presents a literature review on the methodology called Volunteered Geographic Information (VGI) and its use for Landslide Risk Assessment (LRA). General risk assessment procedures are discussed and the potential contributions of VGI are identified, in particular when quantitative characterization of factors such as Hazard, Vulnerability and Exposure is required. The review shows that the standard LRA procedures may benefit from input given by surveyors when performing hazard assessments, while crowdsourced data would be a valuable support in vulnerability/damage assessment studies. The review also highlights several limitations related to the role of VGI and crowdsourcing in LRA.

Keywords: Landslide risk assessment · Geomatics engineering · VGI

1 Introduction

In the last decade, the Volunteered Geographic Information (VGI) tools were indicated as a valuable resource in the evaluation and assessments of risks arising from natural hazards and for a rapid and comprehensive inventory of exposed assets [1,2,3,4,5].

Among the range of possible natural or man-induced disasters, this paper provides a literature review on the possible roles played by VGI and geomatics engineering as support to the Landslide Risk Assessment (LRA) procedure. Initially, possible approaches to the quantitative LRA will be introduced with a short insight to the existing international framework. Successively, a review of useful geomatics engineering techniques, ranging from terrestrial to satellite-based, used in the monitoring of slope failure phenomena will be introduced. Finally, a discussion on the role of VGI and crowdsourcing in the field of LRA will be provided by illustrating issues arisen after the relevant literature.

2 Landslide Risk Assessment: Quantitative Approaches

As presented by the Centre for Research on the Epidemiology of Disasters (CRED) in its annual statistical review, a total of 330 natural triggered disasters were reported in

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2013 [6]. Worldwide, all the monitored phenomena caused 96.5 million of victims (21,610 killed) with a very high percentage (88%) coming from low income economies. The recorded economic damages decreased in comparison to the last decade. Within the wide range of possible natural disasters, the CRED provided a classification that can be found in [1]. Landslides are listed under the geophysical disasters, which caused costs the 82% below their 2003-2012 annual average and mostly due to the Sichuan, China, earthquake. In particular, the geophysical disasters accounted worldwide for 32 episodes (9.7% of total; 7.1 million victims; 1,166 deaths).

As said, many of the geophysical natural disaster were reported over region belonging to developing countries. Here, deficiencies in existing digital maps and assets inventories could represent a limiting factor whenever a quantitative risk assessment procedure is sought.

In the quantitative analysis of risks related to landslide hazards and investigations on slope failure phenomena, an increasing interest has been recently showed by the scientific community and stakeholders. In this field, the assessment of direct and indirect damages to properties and assets take on an increasing importance in addition to the development of reliable procedures and methodologies able to predict potential hazards to landslide. Beside this, increasing attention is now placed in the mitigation procedures able to reduce losses due to landslides by means of effective planning and management processes.

However, in spite of improvements in hazard recognition, prediction, mitigation measure, and effectiveness of early warning systems, worldwide landslide activity is widely reported. For countries affected by landslide risks an improvement in the effectiveness of funds allocation procedures is a requirement in addition to a careful vulnerability assessment of exposed assets. Hazard, risk, vulnerability and exposure are some keywords in the LRA procedure. A detailed list of keywords and definitions was provided in [7] by the United Nations International Strategy for Disaster Reduction.

According to Crozier and Glade [8], the concept of risk refers to a dual component: the likelihood of an adverse happening and its consequences. However, the adverse event has to be recognized and defined as occurrence and consequences triggered by this adverse event. A widely accepted definition of risk is the following: “the exposure or the chance of loss due to a particular hazard for a given area and reference period” [9]. Mathematically, it could be expressed by the multiplication between the probability that a hazard impact will occur and the consequences of such an impact. The Varnes’ formula defines $R = H \times V \times E$, being H the hazard, E the exposure and V the vulnerability components.

In 2009 the UNISDR defines an hazard as “a dangerous phenomenon … that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage”. Moreover, a particular hazard is quantitatively described by the frequency of occurrence of different intensities for different areas. Here, the contributions of surveyors play a fundamental role because of the ability by traditional and novel methodologies to detect and represent the magnitude and spatial pattern of an investigated phenomenon. Scientific studies/maps, long-term monitoring, historic reports on past incidence of hazards (in particular the location), frequency and severity of the events constitute the wide range of useful products for a hazard assessment procedure. In addition, the UNISDR defines the exposures as “people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses”. Exposure is very often referred as “elements at risk”. It is strongly connected with the concept of vulnerability which represents the degree of loss to a given element, or set of elements at risk, resulting from the occurrence of natural phenomena with defined magnitude. The degree of vulnerability could be expressed over a scale ranging from 0 (no damage) to 1 (total loss).

In the quantitative risk assessment, hazard, vulnerability, damage and exposure have to be carefully evaluated with respect to a geographical extent and spatial detail. The relevant literature introduced several approaches to quantitative risk assessment, as summarized in Table 1.

Table 1. Approaches to quantitative risk analysis as found in literature. The table follows an increasing level of complexity of the methodology from top to bottom. In the definition column, common values are introduced only once (after [10], with modifications).

Risk formulation	Definition	Source
Risk = H x C	C: Consequence (potential worth of loss) H: Hazard	Einstein (1988)
Rs = H x V	Rs: Specific Risk V: Vulnerability	Varnes (1984)
Rt = Rs x E = (H x V) x E	Rt: Total Risk E: element at risk	Varnes (1984)
Rt =∑(Rs x E) = ∑ (H x V x E)	V: Vulnerability	Fell (1994)
Rs = P(Hi) x ∑(E x V x Ex) Rt = ∑ Rs (landslide event 1,…n)	P(Hi): Hazard for a particular magnitude of landslide (Hi) E: total value of elements at risk, Ex: Exposure	Lee et Jones (2004)
R(DI) = = P(H) x P(S/H) x P(T/S) x P(L/T)	R(DI): individual risk P(S/H): Probability of spatial impact P(T/S): Probability of temporal impact P(L/T): Probability of loss of life for an individual hazard	Morgan et al. (1992)
R(PD) = = P (H) x P (S/H) x V(P/S) x E	R(PD): Specific risk property P(H): Hazard P(S/H): Probability that landslide impact the property V(P/S):Vulnerability E: Value of Property	Dai et al. (2002)

During the last 10 years, the increasing availability of geographical data, from authoritative sources or crowdsourcing processes, has encouraged the use of statistical and multivariate approaches in the task of hazards/susceptibility prediction to landslide [11]. Investigations related to the landslide susceptibility assessment could be based on qualitative and quantitative approaches (see Figure 1 for an overview).

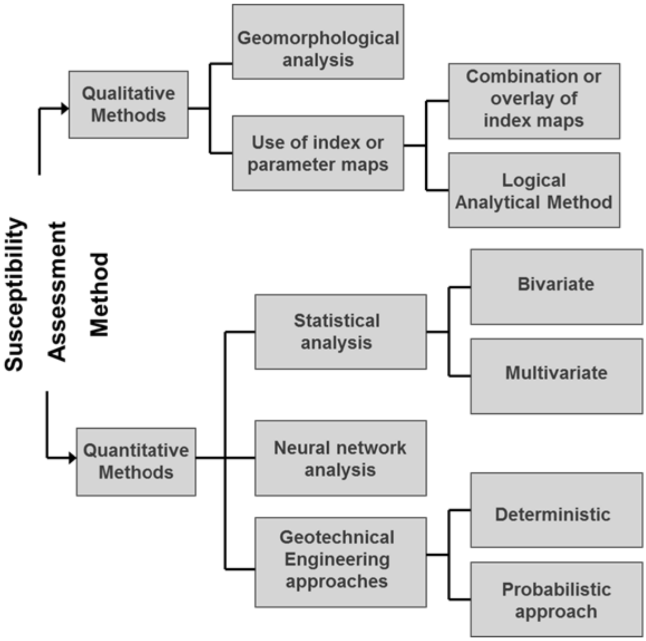

Fig. 1. Classification of landslide susceptibility assessment into qualitative and quantitative approaches

For instance, in the geographical assessment of landslide susceptibility a GIS multivariate analysis could be adopted. In this analysis, possible causal factors have to be related to landslide occurrences.

Causal factors and a reference landslide inventory, where location and description of past occurrences are reported, have to be previously designed within the GIS environment. Causal factors derived from the elevation model are resumed under the term “morphometric”. Others are relevant to lithology, drainage system, existing infrastructures and anthropogenic sources.

In this analysis causal factors have to be connected to landslide occurrences by particular functions whose parameters have to be defined. It follows the idea that “the past are the key of the future”.

The acquisition, storage and management of such data greatly benefits of methodologies provided by geomatics engineering.

3 Approaches by Geomatics Engineering in the Delineation of Landslide Hazard

A comprehensive review of possible methodologies adopted by surveyors in the investigation of slope failure phenomena goes beyond the scope of this work. However, in this sections a gallery of some application of geomatics engineering performed in the past by authors to landslide monitoring and hazard assessment well be provided.

In the LRA, methodologies belonging to the geomatics engineering are mainly focused on the task of detecting hazards due to slow and very slow movements. Among the variety of available techniques the following will be briefly introduced: *real time monitoring by multi sensor approach*, *GNSS (Global Navigation Satellite System)*, *UAV (Unmanned Aerial Vehicle) proximity survey*, *GB-SAR (ground-based radar interferometry)*, *TLS (Terrestrial Laser Scanning)* and *satellite radar interferometry (DInSAR and Permanent Scatterers Interferometry©)*. Geomatics could contributes by providing geographic data on which *statistical and multivariate approaches to landslide hazard prediction* are based on. Hereafter, the above mentioned approaches are very briefly discussed with a pros and cons balance.

3.1 Real Time Monitoring by Multi-sensor Approach

The integration of various techniques is nowadays accessible, allowing to identify possible hazard to slope failures at increasing reliability. By the multi-sensor approach, Automated Total Stations (ATS), GNSS receivers and clinometers represents some of the used technologies.

ATS requires the availability of a suitable site, located outside the affected area, and several reflectors within the monitored zone. Additional reflectors need to be installed over stable positions, serving as control points for data correction. When periodic surveys are required, a forced centering device is often used to assure repeatability of ATS-based positioning. The inter-visibility between ATS and peripheral prisms could represent a drawback in addition to the stability of both the ATS and control prisms [12]. The latter, in particular, if small displacements are sought. To this purpose monuments are checked by GNSS surveys.

The stability of monuments hosting the reference ATS is mandatory and could be achieved by bi-directional clinometer able to measure tilting movements. It contributes to the monitoring of the reference consistency among subsequent observations.

The stability of control prisms is of great concern because their coordinates are used to compute geometric corrections which are subsequently applied to all raw measurements in order to correct refractions effects due the atmospheric influence on the electronic distance measurements. Such errors can achieve some centimeters of magnitude if no correction is introduced. The monitoring station on Figure 2 was designed by authors to detect potential slope failure phenomena in the northern Italian Apennines.

3.2 GNSS (Global Navigation Satellite System)

In the detection of slow and very slow displacements, the GNSS methodology based on the relative-static positioning was globally used by episodic or continuous monitoring. A careful designing of a network, composed of reference and monitoring points at useful locations, is a requirements to understand and model kinematic phenomena. Displacements could be detected at monitoring points (constituting nodes of the network) only and possible instabilities of reference stations established within a 3D reference frame. In the GNSS relative positioning the precision is very high and the error model accurately defined but the number of monitoring points is rather low

Fig. 2. Integrated monitoring system for unstable slopes: master unit at the top; below a GNSS remote site for continuous monitoring, reflectors and reference prism/GNSS

(depending on the spatial point density) and field efforts by surveyors significant. Anyhow, GNSS measurements are able to draw the superficial displacement field at variable (but very often reduced) geographical resolution.

In Figure 3 some results provided by the GNSS monitoring over a small village located in southern Apennines (Italy) are depicted with a delineation of landslides bodies as detected by the geomorphological surveys.

3.3 UAV (Unmanned Aerial Vehicle) Proximity Survey

More recently, multi-rotors UAV systems have proven to be a very useful tool for very high resolution DSM (Digital Surface Model) and orthophotos generation within geomorphological investigations [13,14]. Due to the initial stage of such application to unstable slope, only few of them could be retrieved from literature. See for example [15] for a cutting–edge investigation of sliding phenomena by UAV systems. These UAV-based methodologies use collections of unordered, non-metric, aerial images and data analysis based on classical computer vision approaches.

In particular, the flexible 3D surface reconstruction based on the Structure from Motion (SfM) approach is widely used as rapid, inexpensive and highly automated method. Besides the good quality of elevation model produced, orthophoto at unprecedented spatial resolution can be produced over hazardous area.

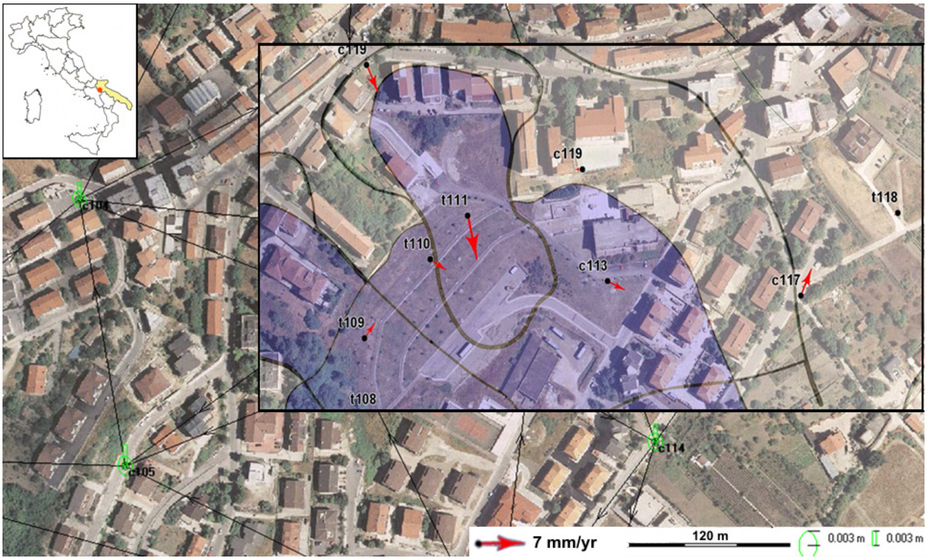

Fig. 3. Displacements over a small portion of the Bovino's (Foggia, Italy) landslide as revealed by the GNSS monitoring. Annual velocities (mm/yr) detected during the year 2009 at nodes and a delineation of the landslide body are superimposed to the GNSS network geometry. Error ellipses are depicted in green (see the reference ellipse in the lower right side).

3.4 GB-InSAR (Ground-Based Interferometric Synthetic Aperture Radar)

Spot monitoring campaigns with GB-InSAR allow the rapid assessment of landslide activity [16] even in radar-hostile, partially vegetated slopes and with high contents of humidity (ground and atmospheric). However, solutions could be affected by the processing strategy due to the parameters used (for instance number/timing of raw scenes, coherence of the images over time and space; shape/extent of the area and number or sampling rate of processed scenes). At very low displacement rates (i.e. few mm during the survey period) and with predominantly vegetated grounds, the processing strategy can affect the outcomes significantly and the detection of small displacements very hard.

Under favorable conditions the installations of GB-InSAR sensors in a suitable place allows the monitoring of slow slope movements in near-real time, being also possible to operate at distances of up to few km from the radar sensor. Results can be visualized "on site" through a 2D/3D displacement map thanks to a GIS interface. See Figure 4 for a displacement map from GB-InSAR data collected at Romanoro (Modena, Italy) with displacement (along the Line Of Sight, LOS) of relevant points (PS) as detected from surveys.

3.5 TLS (Terrestrial Laser Scanning)

With respect to other geomatics techniques, the main advantage in the use of TLS lies in providing a continuous geometric description of surfaces and changes by a multi-temporal

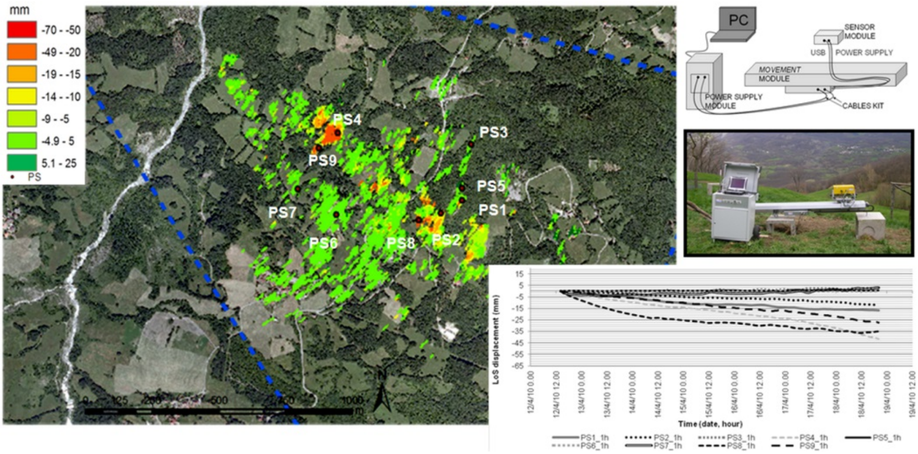

Fig. 4. 2D LOS displacement at Romanoro (Modena, Italy) landslide from processing of GB-InSAR image acquired at 1 hour rate. Time series have been reported for some representative points. In the upper-right insets a depiction of the radar sensors and its components.

approach. The main drawback is the impossibility to identify punctual features at desired locations, resulting in troubles to determine displacements. Despite that, terrestrial laser scanning is widely used to support landslides monitoring and some attempts have been carried out to detect geomorphological changes over time [17].

The main difficulty in comparing successive laser scanning surveys concerns the alignment process. Indeed, the reliability of final results is dependent on the accuracy of alignment process of multiple point clouds. An efficient solution would be the direct alignment, which requests a stable fixed position for the TLS placement at each campaign as well as to fix the orientation by acquiring specific markers during successive surveys. In the indirect approach, a manual or automatic recognition of homologous points on point cloud pairs is required and 3D transformation computed to align point clouds. The vegetation filtering is often required while surveying unstable slopes in order to represent the ground surface only. Once the alignment has been achieved, several strategies are available for surfaces reconstruction: the multi-resolution meshing approach, based on the Delaunay 2.5D triangulation from each scanning position, proved to be more successful in describing complex local morphologies than grid approaches [18]. See Figure 5 for results of TLS surveys to the Collagna (Modena, Italy) rockslide.

3.6 Satellite Radar Interferometry (DInSAR and Permanent Scatterers Interferometry©)

Since 20 years, the satellite sensing based on SAR (*Synthetic Aperture Radar*) technology has been providing valuable information in the LRA. Thanks to methodologies such as the Differential SAR Interferometry (DInSAR) and, more recently, the Permanent Scatterers Interferometry (PSI©), several radar satellites were used to provide impressive information about slow superficial movements. Depending on the

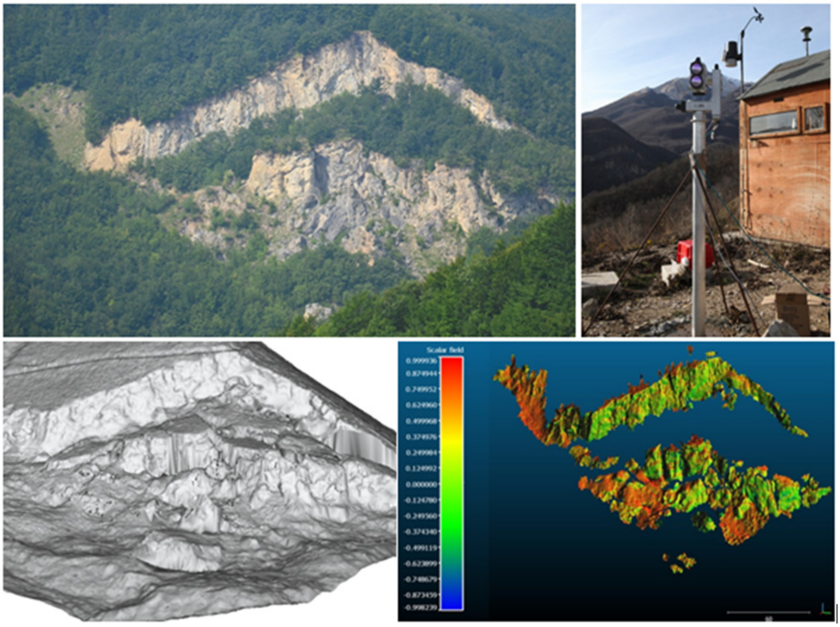

Fig. 5. Results from the Collagna (Modena, Italy) rockslide monitoring (see photograph in the upper left image); the laser scanner during surveying (upper right); Digital Terrain Model obtained by integrating airborne and terrestrial laser scanning (bottom left) and morphological changes over the period 2010-2013 obtained by multi-temporal TLS surveys (bottom right)

geometry of satellite acquisition, elevation maps and deformation maps could be processed by Differential Interferometry. Fringes represent differences in elevations or displacements at large geographical extent.

The alternative PSI© method is based on the statistical analysis of radar response from permanent scatterers with suitable geometry at the ground. A variation in the slant range from satellite to targets among repeated passes is likely due to displacements towards or away from the sensor. Displacements can be solely detected along the LOS and a decomposition of displacements along the vertical and West-Est directions is only possible by the combined analysis of ascending and descending orbits. A potential displacement along a slope will be detected with an opposite sign by the ascending and descending orbits. The methodology is not sensitive to displacements in the north-south direction and over vegetated areas.

4 On the Potential Role of Geomatics Engineering and VGI in the Landslide Risk Assessment Procedure

As stated in section 2, a LRA procedure is a complex task and needs for an integrated approach. According to [19], risk assessment "takes the output from risk analysis and assesses these against values judgements, and risk acceptance criteria". As introduced in section 3, the monitoring of landslide by the geomatics engineering is able to address the complex issues of hazard evaluation and support the census of element at risk. However, an exhaustive LRA could also benefit from community based knowledge. There are several stages at which values and judgments enter in the decision-making process by underpinning consideration about the relevance of risks and the associated consequences. It happens when the identification of a range of possible alternatives for managing risks are formulated. These types of judgment are relevant to the risk evaluation procedure, for instance where three categories of risks could be identified: acceptable, tolerable and intolerable [20].

Such judgments are strongly influenced by psychological, cultural and social perspectives. Hence, a multitude of factors contributes to risk perception, and it may vary greatly among individuals belonging to a community. Therefore, the role played by the "communication of risk" and the "understanding of risk" could be complex.

Despite adversarial attitude and widespread skepticism about the reliability and involvement of the volunteered information, in the framework of the LRA the role of VGI is unquestionably useful under particular conditions. It is the case of rare events, such as those induced or exacerbated by climate change, in which the potential role of individuals may be similar to that played by the early warning system. Under some conditions, the landslide phenomenon may assume an evolution from slow to very fast. Only few slopes could be instrumentally monitored and, in the case of sudden development of the sliding phenomenon, there are no terrestrial or satellite-based methodologies able to provide information at the required temporal rates.

In such situations, information collected from citizens living within areas subjected to landslide risk could help in identifying possible precursory phenomena and constitute a potential early warning system for authorities. These kinds of Community-Based Early Warning Systems (CBEWS) could contribute towards a reduction of economic losses after a natural phenomenon occurs and in the mitigation of direct and indirect effects on goods, people and properties. The CBEWSs are supposed to be an ideal tool, being able to provide the communities and disaster risk manager with anticipatory information on a potential impending phenomenon and improve the preparedness against adverse phenomena. Detractors of such an approach drive the attention on possible false positive responses from CBEWS and the needs of a reliable procedure able to provide a judgment about the credibility of information from the users.

The VGIs philosophy could support EWS especially in developing countries where inventories, existing data infrastructures and available equipment are not able to cope with a rapid and widespread monitoring of emergency situations. Even though a risk evaluation can be conducted with data from instrumental survey and monitoring procedures, a complete LRA needs the implementation of intangible data. The latter could be based on the knowledge by communities about the specific risk. Obviously, an integration between expert and community based knowledge could be also an opportunity. Risk maps developed through collaboration between researchers and communities are the simplest way to represent and inform about a specific risk. Beside this, a detailed description of the whole process would be useful in addition to guidelines to support any decisional phase.

Due to thsese motivations, the LRA could greatly benefits from massive information coming from crowdsourcing, technical and/or scientific knowledge and VGI. In the hazard assessment procedures surveyors coming from professional or scientific communities can be a primary source of knowledge by providing the extremely wide variety of data and results on the magnitude and extent of monitored phenomena. Open problems are related to the way surveyors can disseminate data, results and knowledge about surveyed hazards. A common practice about dissemination of data would be required by taking also into account issues related to the data heterogeneity (arising from different methods, production stage, etc.) and varying level of uncertainty of observation and results.

In view of expected implementations of VGI systems as a tool for risk assessment to such phenomena, some open questions have to be faced. A first one is related to the minimum level of skillfulness and knowledge required by contributing people while a second relies with the amount and reliability of available information, especially over highly vulnerable areas with poor dataset or within regions where geographical database are not in use. Several other task have to be faced thoroughly: the willingness by users to contribute, difficulties in the access to knowledge by potential contributors (critical for poor qualified group of people), the reliability of contributions and to the need of a long-term maintenance of initiatives. Nevertheless, the introduction of the VGI concepts could be a solution for some of the issues arisen in this paper. For instance, it is a shared opinion that the conceptual match between elements at risk and VGI is an applicable framework.

5 Conclusion

In the scientific community involved in the field of risk assessment related to natural disasters is a common thought the VGI could be a solution for some of the tasks. In particular, the Landslide Risk Assessment procedure may benefit from the use of VGI and crowdsourcing in the strengthening of existing Spatial Data Infrastructures and "authoritative" or "conventional" data and whenever data are missed.

Nevertheless, limitations to the use of VGI in the natural disaster can be found in recent literature. Firstly, some gaps in the use of VGI for natural hazard assessment must be filled as well as the need for more robust case studies and experimental research to support this promising field [1]. Manfré et al. [2] introduced the needs of training for involved volunteers and minimum number of volunteers. Another key aspect was introduced in [21] by Camponovo and Freundschuh who discussed the need for more research on the quality of the categorization (i.e., attribute data) of volunteered emergency data. Coleman [22] stated that the VGI is not the ultimate solution to all geospatial data updating and maintenance challenges now faced by mapping organizations. The contribution of the scientific community in this field could be placed in the establishment of a rigorous framework and workflow able to provide reliable results and reduce the uncertainty of basic information used in the Landslide Risk Assessment procedures.

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