MONITORING OF SLOPE MOVEMENTS COUPLING AUTONOMOUS WIRELESS SENSOR NETWORKS AND WEB SERVICES

K. Smarsly[1], K. Georgieva[2], M. König[2] and K. H. Law[1]
[1] Department of Civil and Environmental Engineering,
Stanford University, Stanford, CA, USA
[2] Department of Civil and Environmental Engineering,
Ruhr-Universität Bochum, Bochum, Germany

ABSTRACT

Slope movements have caused severe damages of civil infrastructures and numerous human fatalities. Continuous monitoring of slope movements and the collection of vital landslide information are beneficial for the assessment of landslide hazard and risk. With the advances in wireless communication and Internet technologies, it becomes possible to continuously collect and assess landslide information, which can help to better understand landslide processes and to reliably issue early warnings. This paper presents the prototype development of an autonomous monitoring system for slope movements that couples wireless sensor networks and web services. Wireless sensor nodes are distributed in the field to autonomously collect and analyze sensor data taken from the observed slope. Embedded into the wireless sensor nodes are autonomous software units, referred to as “software agents”, that are capable of automatically assessing the sensor data and sending alerts if abnormal slope behavior is detected. The wireless sensor network is remotely connected to an Internet-enabled early warning and information system, which integrates geospatial information from external geographic information systems (GIS) and provides real-time slope information to human individuals.

KEYWORDS

Monitoring, slope movements, landslide forecasts, early warning systems, wireless sensor networks, remote sensing, web services, software agents

INTRODUCTION

Increasing numbers of natural and anthropogenic hazards, causing significant damages to civil infrastructures, have been observed in the last years (Guha-Sapir *et al.* 2011, 2012). In particular, landslides, i.e. mass of earth material displaced by gravity, have caused severe damages and enormous costs. Landslides do not necessarily occur suddenly. The velocities of slope movements differ significantly depending on the slope material (such as bedrock, debris, or earth) and on the types of landslide, e.g. fall, topple, slide, spread, or flow (Cruden and Varnes 1996). Whereas earth slides may continue to move constantly only a few millimeters per year, rock falls, by contrast, may develop only a minimal instantaneous movement before collapsing suddenly at several meters per second (Varnes 1978). In Maierato (Italy), for example, more than 2,300 people have been evacuated in time before a breakaway of a slope occurred, followed by a rotational slide and a debris flow (Guerricchio *et al*. 2011; BGS 2010).

Landslide forecast methods, according to Busslinger (2009), can be divided into *long-term forecasts* and *mid- and short-term forecasts*. Long-term forecasts can indicate potential hazards several years in advance of an event; usually, landslide inventories and hazard maps, to be interpreted by geologists, are compiled using digital tools such as geographic information systems (GIS), Light Detection and Ranging (LiDAR), or Interferometric Synthetic Aperture Radar (InSAR). Mid- and short-term forecasts, on the other hand, allow calculating landslide predictions within lead times of years to months (mid-term forecasts) and months to days (short-tem forecasts). According to Busslinger (2009), there exist two major groups of state-of-the-art methods both for mid-term forecasts and for short-term forecasts: forecasts based on climatic conditions and monitoring-based forecasts. Forecasts based on climatic conditions typically analyze rainfall, which is the most common trigger of landslides (Wieczorek and Guzzetti 2000; Tohari *et al*. 2007; Brunetti *et al*. 2009, 2010). Monitoring-based forecasts measure different parameters in the slope, such as deformations (or velocity), pore water pressure, microseismics, or water content. Depending on the parameters of interest, several types of sensors are installed in the slope – extensometers, inclinometers, accelerometers, tiltmeters, seismic instruments, acoustic emission systems, etc. – and connected, usually via cables, to data acquisition units located on-site. It should be noted that, regardless of the forecast method applied, it is not sufficient to solely collect and analyze sensor data when trying to make reliable landslide forecasts. A comprehensive examination of regional conditions as well as site observations (e.g. intensity and duration of precipitation, groundwater level variations, seismic activities, stream and river erosion) and knowledge about potential landslide triggers (e.g. rainfall, snowmelt, volcanic eruption) are necessary to ensure the success of the forecast method(s) applied.

With the advancements in sensor technologies, monitoring-based forecast methods have proven to be reliable and cost-efficient (Wieczorek and Snyder 2009). Monitoring-based methods are capable of providing valuable data sets taken from the slope that can help not only to predict future landslide events and to improve existing landslide inventories, but also to better understand the landslide processes. Although the enormous potential of landslide monitoring systems for hazard and risk reduction is evident (USGS 2011, Reid and LaHusen 1998), the application of monitoring systems for landslides, and for slope movements in general, is still in its infancy. Integrated monitoring systems coupling autonomous wireless sensor networks and web services have yet to be developed. The United Nations Office for Disaster Risk Reduction in its 2006 Global Survey of Early Warning Systems (UNISDR 2006) concludes "that there are many gaps and shortcomings" with respect to monitoring systems for slope movements, although "the signs of ... a landslide can often be detected at an early stage and used for warnings". This paper describes the design and implementation of an autonomous monitoring system for slope movements. Two main components of the monitoring system, an autonomous wireless sensor network and an early warning and information system are presented and validated through a laboratory experiment. The paper concludes with a summary and a brief outlook on future research directions.

DESIGN AND IMPLEMENTATION OF THE MONITORING SYSTEM

The architecture of the monitoring system is shown in Figure 1. The monitoring system is composed of two main components, the autonomous wireless sensor network (WSN) and the early warning and information system (EWIS), which are briefly described in the following subsections.

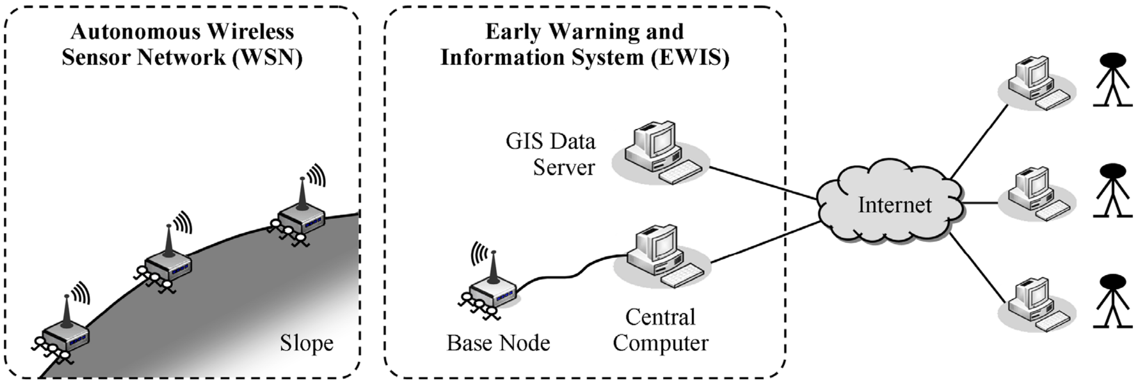


Figure 1 Architecture of the monitoring system

Autonomous Wireless Sensor Network (WSN)

The wireless sensor network is designed to continuously collect and analyze sensor data taken from the monitored slope. The wireless sensor network comprises of several wireless sensor nodes that communicate with each other and, through a base node, with the early warning and information system (Figure 1). The wireless sensor nodes deployed for the prototype implementation of the WSN include internal 3-axis accelerometers. Acceleration measurements are continuously recorded and analyzed directly on the nodes to detect abnormal slope movements. If (potential) anomalies are detected by a wireless sensor node, further activities are automatically triggered; for examples of the triggered activities, the sampling rate of the sensor node is increased or other sensor nodes are requested to take action, e.g. to increase their sampling rates or to perform specific data analyses on demand. In addition, alerts are sent to the early warning and information system in order to issue early warnings and to inform human individuals about the potential anomalies. For the automated detection of slope movements using acceleration measurements, two well-established forecast methods are combined and embedded into the wireless sensor nodes; these are based on (i) calculations of tilt values of the wireless sensors and (ii) the inverse values of surface displacement velocity of the slope.

Tilt measurements are usually performed to estimate the stability of an indistinct landslide, or to examine landslide potentials, typically on a daily basis (Marui 1988). Here, tilt values are calculated primarily to detect movements through changes in the orientation of the wireless sensor installed in the slope. The tilt values are calculated using the basic trigonometric equations

$$\rho = \arctan\left(\frac{A_X}{\sqrt{A_Y^2 + A_Z^2}}\right) \quad (1)$$

$$\phi = \arctan\left(\frac{A_Y}{\sqrt{A_X^2 + A_Z^2}}\right) \quad (2)$$

$$\theta = \arctan\left(\frac{\sqrt{A_X^2 + A_Y^2}}{A_Z}\right) \quad (3)$$

where A_i are the accelerometer outputs of a wireless sensor node in x, y and z direction, ρ is the pitch, defined as the angle of the x-axis relative to the ground, ϕ is the roll, defined as the angle of the y-axis relative to the ground, and θ is the angle of the z-axis relative to gravity. The tilt values, being computational efficient, serve in this study as a trigger to initiate the calculations of the inverse values of surface displacement velocity if significant changes of the sensor orientations, i.e. surface movements, are detected.

Calculations of the inverse values of surface displacement velocity, referred to as "inverse velocity method", require more computational effort and a higher sampling rate than the calculations of tilt values. However, unlike tilt values, the inverse velocity method provides accurate predictions of the slope failure time in the event of slope movements (Rose and Hungr 2006). Evidently, if the velocity of surface displacement v of a slope surface increases over time, its inverse v^{-1} decreases, and when v^{-1} approaches zero, slope failure occurs. Figure 2 shows the inverse of surface displacement velocity plotted against time. The curves in Figure 2 can be described by the following equation (Fukuzono 1985):

$$v^{-1} = \{a(\alpha - 1)\}^{\frac{1}{\alpha-1}} \cdot (t_f - t)^{\frac{1}{\alpha-1}} \quad (4)$$

where v is the velocity of surface displacement, calculated by the sensor nodes through numerical integration of the acceleration measurements, a and α are constants depending on the slope characteristics and t_f is the failure time. Fukuzono (1985, 1987), who first introduced the inverse velocity method in 1985 for predicting rainfall-induced landslides, distinguishes three shapes of the curves. For a linear curve (α=2), the failure time t_f can exactly be predicted using two points. Although several authors have shown that the curves would typically be expected to be linear (Voight 1989, Kilburn and Petley 2008), it is also possible to relatively accurately estimate the failure time for curves being convex (α>2) or concave (α<2) by calculating the point at which the tangent line of the curve crosses the axis of abscissa. For the prototype implementation on the WSN, linear curves are assumed.

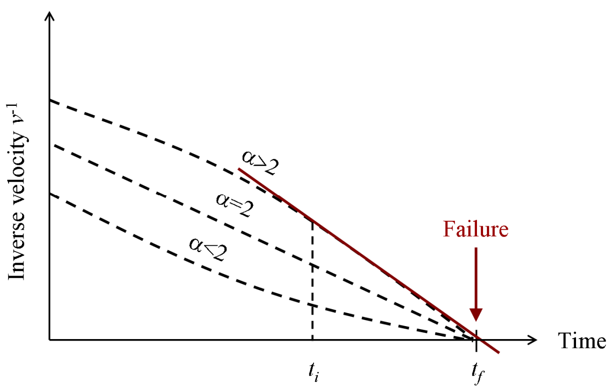


Figure 2 Typical curves of the inverse values of surface displacement velocity before slope failure

The forecasting methods described above are embedded into the wireless sensor nodes by means of software agents. A software agent is an autonomous, flexible software program able to cooperate with other software agents and to complete a specific task without direct human intervention (Wooldridge 2002). By deploying cooperating software agents that analyze the slope parameters in a decentralized fashion and communicate their findings with each other, the overall system performance and flexibility can considerably be enhanced. Figure 3 shows some of the software agents embedded into the wireless sensor nodes. Every agent is responsible for executing one specific monitoring task, for example calculating the tilt values and the (inverse) velocity from the acceleration measurements (“TiltSamlper” and “VelocitySampler” agent), analyzing the collected data sets (“TiltAnalyzer” and “VelocityAnalyzer” agent), or communicating the data to other wireless sensor nodes and, via the base station, to the early warning and information system (“Communicator” agent).

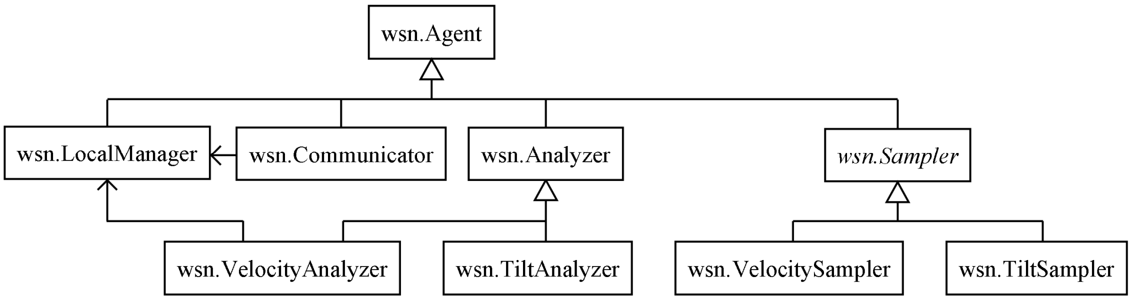


Figure 3 Software agents embedded into each wireless sensor node

Early Warning and Information System (EWIS)

The early warning and information system (EWIS) is designed to provide real-time information about the observed slope and to issue warnings if abnormal slope movements are detected. The prototype EWIS is primarily implemented on a central computer that is connected to the WSN through a base station (Figure 1). The software installed on the central computer is composed of three major system components. First, a *MySQL database* is deployed for persistent storage of the data sets. Describing the organization of the data sets, the database schema, which includes tables for sensor nodes, tilt (and tilt variation), velocity and acceleration measurements, is shown in Figure 4. The second system component is a *controller* implemented in Java, which is primarily designed for retrieving the data sets from the WSN, for analyzing the data, converting it, and writing it into the database; the controller represents a central interface between the WSN, the database and the third major system component, a *web service*.

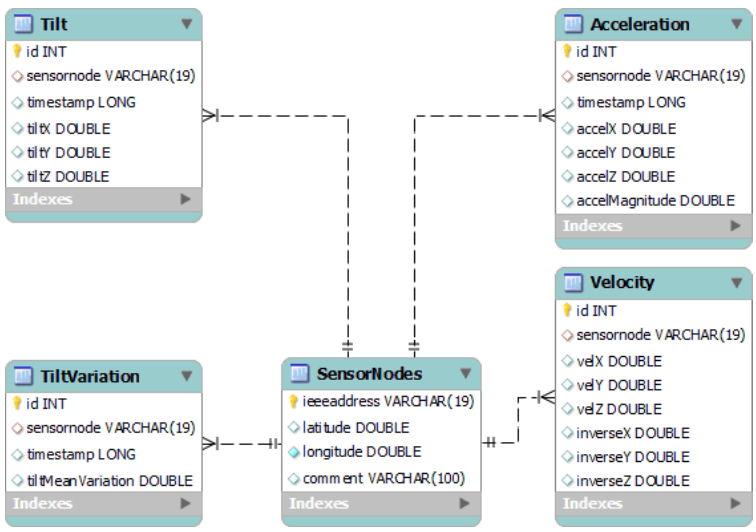


Figure 4 Database schema for the prototype EWIS implementation

The purpose of the web service is manifold; it is designed to ensure Internet-based remote access to the EWIS, to provide slope information in real time, to disseminate early warnings in case of abnormal slope movements, and to allow (authorized) users communicating with the WSN, e.g. to request measurements for a specific sensor. Technically, the web services are implemented using “JavaServer Pages” technology and the “Apache Tomcat” open source web server. Figure 5 shows exemplarily a website that is dynamically generated by a web service during system tests using simulated data. The website, which serves as a graphical user interface (GUI) for remote access to the EWIS, provides on the left hand side real-time plots of the data sets retrieved from the WSN (such as tilt, velocity, and acceleration). As shown on the right hand side of Figure 5, the user can graphically select sensors and view sensor data in a geospatial context by choosing the sensors of interest using markers in dynamic, aerial maps. The aerial maps as well as geospatial information, such as latitude and longitude of each sensor location, are integrated into the website using the “Google Maps API”. In addition to the visualization of sensor data, functionalities are implemented into the website to create reports on the slope conditions and to automatically send email alerts if abnormal slope movements are detected.

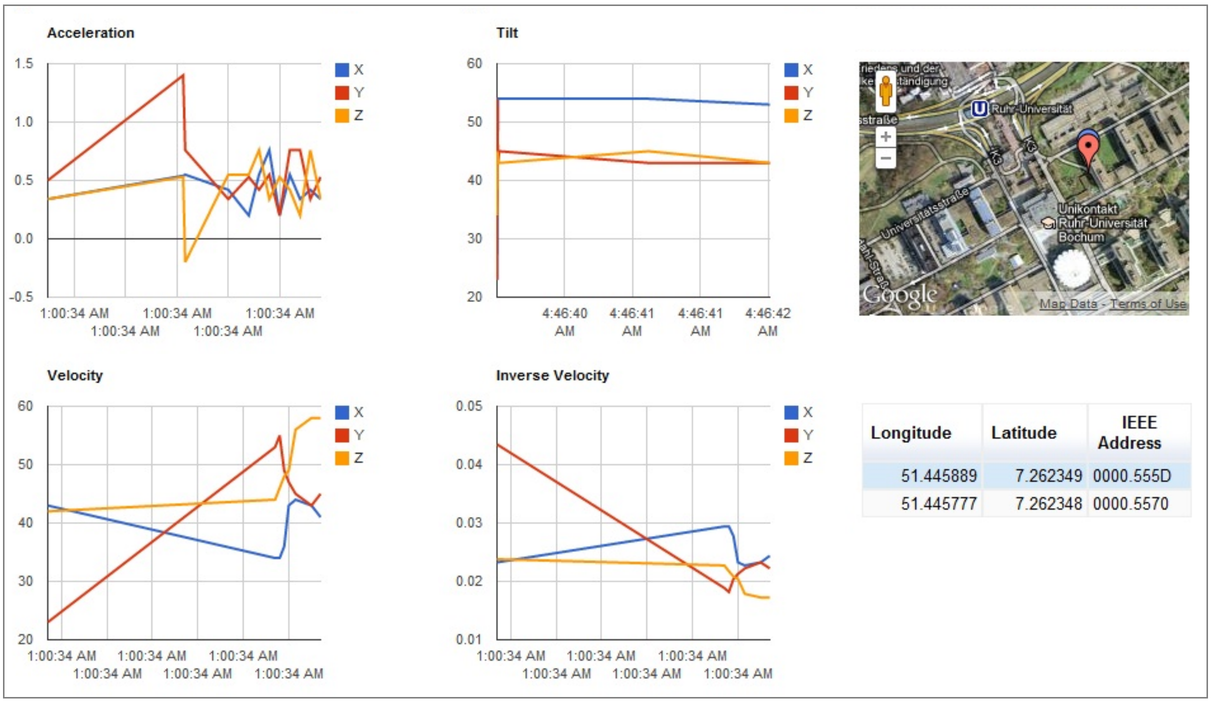
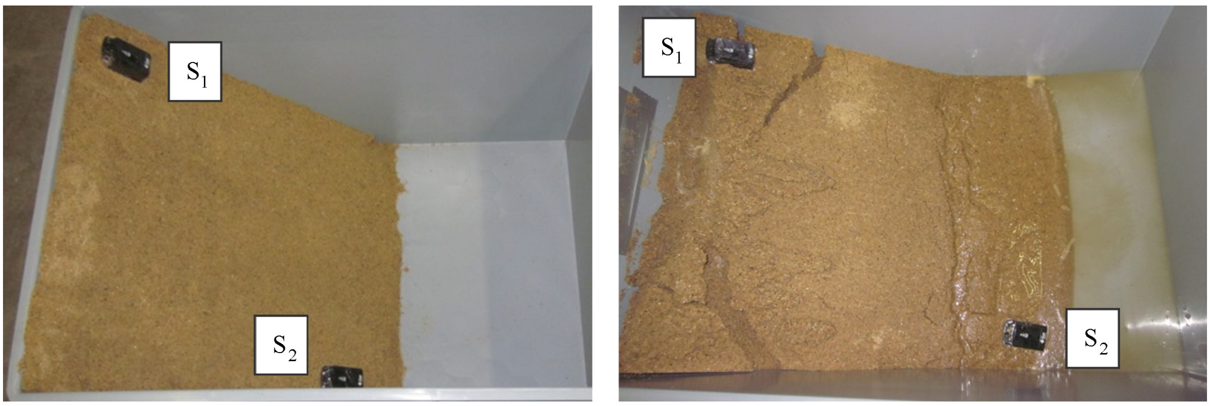


Figure 5 Preliminary website integrating sensor data and GIS data for remote monitoring (using test data in the laboratory)

LABORATORY EXPERIMENT

A laboratory experiment is conducted at the Ruhr-University Bochum. Besides the proof of concept of the newly implemented agent-based approach, the major goal of the experiment is to validate the capability of the monitoring system to autonomously detect slope movements and to issue warnings if necessary. Furthermore, the Internet-based real-time monitoring is of interest. For the experiment, a container is filled with sand as illustrated in Figure 6a. A sand slope is constructed with an inclination of α_m=45°, a bulk density of ρ_b=1.56 g/cm^3, and a void ratio of e=0.7. Two wireless sensor nodes, S_1 and S_2, are installed on the top and at the toe of the slope surface. During the experiment, the wireless sensor nodes, each of which hosting the embedded software agents, are communicating with each other and, through the base station, with the EWIS installed on a laptop computer. The embedded software agents in each wireless sensor node measure the acceleration in periodic intervals, calculate the tilt values, and send the data sets to the connected EWIS where it is stored in the database.



(a) (b)

Figure 6 Sand slope experiment conducted in the laboratory: (a) before failure, (b) after failure

To simulate rainfall, water is poured onto the slope surface. After pouring 10 liters of artificial rainfall, the soil is saturated and a slow movement starting at the toe of the slope is observed by the monitoring system. Thereupon, tension cracks occur. The slope movement is reflected in changes of the measurement data, as identified by the software agents. As a direct consequence, the sensor sampling rate is automatically increased, a warning is generated, and the inverse of surface displacement velocity is calculated and sent to the EWIS, which provides the data in real time through the dynamic website described above. Finally, after a total of about 14 liters of water cracks occur at the top of the slope leading to a total slope failure (Figure 6b). In conclusion, the laboratory experiment has demonstrated that the monitoring system (i) autonomously detects abnormal slope movements and (ii) generates landslide forecasts, i.e. failure time predictions, as well as early warnings that are remotely available through the Internet.

CONCLUSIONS

The development of an autonomous monitoring system for slope movements, which couples autonomous wireless sensor networks and web services, has been presented. Geospatial information, taken from an external geographic information system (GIS), has been integrated into the monitoring system. Capable of remotely monitoring slope movements, the monitoring system provides real-time slope information and supports human individuals in assessing hazard and risk of landslides. Compared to traditional, cable-based approaches towards monitoring slope movements, significantly reduced installation and maintenance costs are achieved due to the utilization of wireless sensor networks. Furthermore, the amount of sensor data to be transmitted is considerably reduced because of the decentralized on-board processing of sensor data performed by the software agents embedded into the wireless sensor nodes. In future research efforts, the approach presented in this study can further be improved by measuring additional parameters such as rainfall, soil moisture, or surface displacement. Furthermore, the integration of external weather data may help to further increase the reliability and precision of the landslide forecasts and early warnings issued by the monitoring system. Finally, large-scale field experiments are scheduled to be conducted at the Ruhr-University Bochum, and for the simulation of rainfall-induced slope failure, large-scale slope models are to be deployed to further validate and optimize the proposed monitoring concepts.

REFERENCES

British Geological Survey – BGS (2010). ”Landslides around the world – Maiereto landslide Italy, Calabria, 2010”. *Documentation*. Online: http://www.bgs.ac.uk/discoveringGeology/hazards/landslides/world.html (Accessed: July 26, 2012). Nottingham, UK: British Geological Survey – Natural Environment Research Council.

Brunetti M.T., Peruccacci S., Rossi M., Guzzetti F., Reichenbach P., Ardizzone F., Cardinali M., Mondini A., Salvati P., Tonelli G., Valigi D. and Luciani S. (2009). ”A prototype system to forecast rainfall induced landslides in Italy”. In: *Proceedings of the First Italian Workshop on Landslides*. Naples, Italy, 2009.

Brunetti M. T., Peruccacci S., Rossi M., Luciani S., Valigi D. and Guzzetti F. (2010). ”Rainfall thresholds for the possible occurrence of landslides in Italy”. *Natural Hazards and Earth System Sciences*, 10, pp.447-458.

Busslinger, M. (2009). ”Landslide time-forecast methods - A literature review towards reliable prediction of time to failure”. *Report*. HSR University of Applied Sciences, Rapperswil, Switzerland.

Cruden, D.M. and Varnes, D.J. (1996). ”Landslide Types and Processes”. In: *Landslides Investigations and Mitigation*. Transportation Research Board, Special Report No. 247, Washington, DC, USA.

Fukuzono, T. (1985). “A New Method for Predicting the Failure Time of a Slope”. In: *Proceedings of the IVth International Conference and Field Workshop on Landslides*. Tokyo, Japan, 1985.

Fukuzono, T. (1985). “Experimental study of slope failure caused by heavy rainfall”. *Proceedings of the Corvallis Symposium – IAHS Publ*., 165, pp. 133-134.

Guerricchio, A., Doglioni, A, Fortunato, G., Guglielmo, E., Ponte, M. and Simeone, V. (2011). ”The influence of deep seated gravitational slope deformation in the activation of the large Maierato landslide in 2010”. In: *Proceedings of the Second World Landslide Forum (WLF2)*. Rome, Italy, 2011.

Guha-Sapir, D., Vos, F., Below, R. and Ponserre, S. (2011). “Annual Disaster Statistical Review 2010”. *Report*. Brussels, Belgium: Centre for Research on the Epidemiology of Disasters (CRED).

Guha-Sapir, D., Vos, F., Below, R. and Ponserre, S. (2012). “Annual Disaster Statistical Review 2011”. *Report*. Brussels, Belgium: Centre for Research on the Epidemiology of Disasters (CRED).

Kilburn, C.R.J and Petley D.N. (2003). “Forecasting giant, catastrophic slope collapse: lessons from Vajont, Northern Italy”. *Geomorphology*, 54(1-2), pp. 21-32.

Marui, H. (1988). “FAO watershed management field manual: Landslide prevention measures”. Rome, Italy: Food and agriculture Organization of the United Nations, 1988.

Reid, M.E. and LaHusen, R.G. (1998). "Real-time monitoring of active landslides along highway 50, El Dorado County". *California Geology*, 51(3), pp. 17-20.

Rose, N.D. and Hungr, O. (2006). "Forecasting potential slope failure in open pit mines using the inverse-velocity method". *International Journal of Rock Mechanics and Mining Sciences*, 44(2007), pp. 308-320.

The United Nations Office for Disaster Risk Reduction – UNISDR (2006). "Global Survey of Early Warning Systems". Online: http://www.unisdr.org/2006/ppew/info-resources/ewc3/Global-Survey-of-Early-Warning-Systems.pdf (Accessed: July 26, 2012). Geneva, Switzerland: United Nations Inter-Agency Secretariat of the International Strategy for Disaster Reduction, International Environment.

Tohari A., Nishigaki M. and Komatsu M. (2007). "Laboratory Rainfall-Induced Slope Failure with Moisture Content Measurement". *Journal of Geotechnical and Geoenvironmental Engineering*, 133(5), pp. 575-587.

U.S. Geological Survey – USGS (2011). "Real-Time Monitoring of an Active Landslide above U.S. Highway 50, California". *Online Monitoring system*. Online: http://landslides.usgs.gov/monitoring/hwy50 (Accessed: July 26, 2012). Denver, CO, USA: U.S. Geological Survey - National Landslide Information Center.

Varnes, D.J. (1978). "Slope movement types and processes". In: *Landslide Analysis and Control*. Transportation Research Board, Special Report No. 176, Washington, DC, USA.

Voight B. (1989). "A relation to describe rate dependent material failure". *Science*, 243(4888), pp. 200-203.

Wieczorek G.W. and Guzzetti F. (2000). "A review of rainfall thresholds for triggering landslides". In: *Proceedings of the EGS Plinius Conference*. Maratea, Italy, 1999.

Wieczorek, G.F. and Snyder, J.B. (2009). "Monitoring slope movements". In: Young, R. and Norby, L. (eds.) *Geological Monitoring*. Boulder, CO, USA: The Geological Society of America.

Wooldridge, M. (2002). *An Introduction to MultiAgent Systems*. West Sussex, UK: John Wiley & Sons, Ltd.