Monitoring and Modeling of Landslide in Earthquake Environment

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Abstract: Besides precipitation, a major trigger for landslides is earthquake. Landslides triggered by earthquake always cause significant fatalities and economic loss. Therefore it is needed to improve basic understanding of the technical, financial and social risks posed by earthquakes triggered landslides. Furthermore basic understanding of processes and cascading hazards related to earthquake triggered landslides must be enhanced. Recent research in the area of real-time monitoring of landslides development focus on the application of micro sensors (MEMS) in ad hoc wireless sensor networks operated in an interoperable spatial data infrastructure (SDI) according to the sensor web enablement (SWE) guidelines of the OGC (Open Geospatial Consortium), like the SLEWS-Sensor based Landslide Early Warning System. Apart from motion detection, the SLEWS sensor nodes also provide a 3D acceleration data to evaluate direction and value of the peak acceleration. This information can be used in an event case both to monitor endangered slopes or critical infrastructures and to initiate warnings of rail or road blocks. Furthermore the data from the sensor network can be provided in real-time for shake or alert maps via standardized interfaces. In this paper, through comparison of numerical solutions and real-time data, the mechanical parameters can be inferred by inversion method, which are in turn to determine the safety factor or the reliability degree of slopes needed in DIN 1054.

Keywords: wireless sensor network, MEMS, earthquake, landslide monitoring, acceleration measurements, numerical simulation

1. Introduction

Due to the progressive development of urban areas and infrastructure, more and more people settle in environments that are or become endangered by landslides. Apart from socio-economic factors, extreme weather conditions and earthquake are the main reasons for this ascent. Therefore, prevention and management of landslides are in an urgent focus today. There is a need to improve basic understanding of the technical, financial and social risks posed by landslides. Especially, due to the rising vulnerability of the population to landslide hazards, the demand and requirements for early warning and monitoring systems continuously grow at the same time (Azzam et al., 2011).

The high relevance of this topic can be seen from the fact that early warning and early action are selected as the two focus topics of the World Disaster Report 2009. Even so the number of disastrous events over the last 30 years rose, the decline of injuries, loss of livelihood and fatalities is seen at least partly as a result of the improved early warning capabilities in this period (IFRC, 2009). Over last decade (1999 -2008) still the largest number of fatalities is related to landslide disasters and related phenomena (IFRC, 2009). Besides precipitation triggered landslides,
earthquake triggered landslides account for the majority of catastrophic landslides. Youd (1978) for instance states that about 56% of the total costs of the 1964 Alaska earthquake were related to seismically triggered slope failures. More recent disasters like the Chi-Chi earthquake 1999 and the Wenchuan earthquake 2008 prove this and show the need to extend the efforts for earthquake protection measures on slope and ground instabilities. During wenchuan earthquake more than 56,000 landslides were triggered in steep mountainous terrain covering an area of about 41,750 km$^2$ (Dai et al., 2011). The earthquake-induced landslides produced extensive damage to housing settlements and irrigation channels. Highways and bridges were blocked or destroyed which result in the city of Wenchuan and many other towns became isolated, which greatly frustrated rescue and relief efforts. In additional the landslide dams generated 34 large barrier lakes that threatened the residents who lived downstream of these dams (Cui et al., 2009; Tang et al., 2009). The earthquakes destroy the vegetation and material structures of hill slopes, and left the affected area with a higher risk on the landslide or debris flow hazard.

For this purpose a new type of environmental sensor network is necessary, which can provide on-line real time data retrieval without cable connection in potential landslide area. Resent research of sensor network development focus on the integration of micro sensors (MEMS) in ad hoc wireless sensor networks for real-time monitoring, which can be operated in interoperable spatial data infrastructures (SDI) according to the sensor web enablement (SWE) guidelines of the Open Geospatial Consortium (OGC) (Arnhardt et al., 2007; Fernandez-Steeger et al. 2009). An example of this type modern environmental sensor network is described as SLEWS-Sensor based Landslide Early Warning System providing motion detection with position sensors as well as 3D acceleration data (Klapperich et al., 2011).

Real-time monitoring systems can help people to understand the failure mechanisms of slopes induced by heavy rainfall or earthquake, and invert the input parameters of the slope stability analysis model. Through comparison of numerical solutions and real-time data, the mechanical parameters can be inferred by inversion method, which are in turn to determine the safety factor or the degree exploitation needed to DIN 1054. In this paper, approaches are possible as shown by coupling of real-time sensor data and numerical simulations, to elevate the accuracy of slope stability analysis.

2. Real time sensor network

One major demand in hazard monitoring is the fast and reliable data retrieval to evaluate the current situation in the monitored area. Nowadays wireless sensor networks (WSN) can provide an important contribution to reach that aim. Therefore, the joint project “Sensor-based Landslide Early Warning System” (SLEWS) aims at real-time monitoring using WSN for different types of landslides, which is the development of a prototypic Alarm and Early Warning system (EWS) (Arnhardt et al., 2007). A WSN consists of a number of sensor nodes and a data collecting point, so called the gateway (Fig. 1). It is possible to monitor different active phenomena. Sensor nodes can interact with their neighbor nodes and perform simple data processing. Each node has its own power supply, transmission and receiving unit,
microprocessor, and internal memory. The nodes seek for the best data routing independently. If a connection fails, the routing will be adapted automatically (self-healing). Data from each node is sent to the gateway via radio directly or via other nodes (multi-hop).

![Figure 1: Structure of an ad hoc wireless sensor network (Fernandez-Steeger et al., 2009)](image)

This setup allows an independent working from other nodes of the WSN and permits a stable runtime. The Multi-Hop function reduces the requirement for long-range transmission and in turn also the transmission power (Sohraby et al., 2007). Due to the ad-hoc character of the self organization, new nodes or temporarily disconnected nodes can easily connect and synchronize themselves with the system (Fig. 1). The sensor network used in the SLEWS project uses the 868 MHz frequency band for sending radio signals. Data rates range from 4.8-115kbits/s at transmission distances from 10 m to 1.2 km (Fernandez-Steeger et al., 2009).

For the detection and direct monitoring of different kinds of landslide processes and deformations, a new sensor board was developed (Fig. 2). It includes the measuring sensors (acceleration, inclination and a barometric pressure sensor) and the node for data and command transfer. Due to the modular setup of the hardware, it is easy to adapt or integrate the components in existing solutions. Either batteries (battery pack) or solar powered (solar module) rechargeable batteries (Fig. 2) can be used for the power supply of the nodes. The gateway can be connected to a DC energy source (6 or 12 V), fuel cell or solar panel (Solar gateway). This system is connected either to an existing telemetric unit or via GSM/GPRS to the internet and subsequently to a data infrastructure to process the sensor data. To extend the stand time and reduce maintenance of the system, the nodes can be operated in different energy-saving modes. This system also has a property of Bi-directional structure, which means nodes can not only transmit data, but also operators can reconfigure the nodes, for example, sampling rate of sensors, or turn off sensors to reduce energy demand, send upgrades or make data requests. This bi-direction communication allows users to remote control and updates the system.
The signals from the sensor network can be collected at the gateway and transmitted from there to the server for data retrieval and processing (Fig. 3). Here a special programmed protocol (the transmit receiver unit) feeds the data into a SQL-database. Further feeder applications may be installed to transfer the data to further data applications. To provide and compute the data in a spatial data infrastructure according to Open Geospatial Consortium (OGC) standards, a feeder service with an appropriate compiler can be used to store the data in a post GIS spatial database (Fernandez-Steeeger et al., 2009). The database might be used as a source for a Sensor Observation Service (SOS) to retrieve the data standardized. The advantage of this type of data representation is that any user or application using proper query syntax is able to access data sets without previous knowledge. Furthermore, event-based notification can be pushed asynchronously using a Sensor Alert Service (SAS) to draw user’s attention in case of thresholds exceeded or system alerts.

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**Fig. 2** Components of the SLEWS sensor network

**Fig. 3** Workflow for data integration of the sensor network into a spatial data infrastructure (SDI) according to OGC standards
Generally to speak, the advantages of this type of sensor network are real-time ability, self-organization and self-healing capacity, energy efficiency, bi-directional communication skills and open data interfaces allowing the easy integration of the system in an SDI (Walter and Nash, 2009).

3. Micro sensors in SLEWS

Landslides are complex ground movements that cause deformation and displacement on the surface as well as damage to constructions. In the case of seismically landslides, besides the displacement, seismic shaking or ground acceleration also can be monitored by sensors. Except high precision, sensors in a WSN have to fulfill further specific requirements. They should be small in size, have low energy consumption, provide digital interfaces and inexpensive to use them in large quantities. Nowadays Micro-Electro-Mechanical-Systems (MEMS) can support this effort, because they satisfy all of these requirements. The MEMS sensors integrate very small mechanical and electronic units, sensing elements and transducers on a small microchip. In the SLEWS system, 3D MEMS silicon capacitive sensors made of single crystal silicon and glass for measuring acceleration, tilting and barometric pressure are used (Fig. 4).

The 3D acceleration sensor has a sensitivity of 1333 counts/g and an acceleration range of ± 2g. To monitor changes of sensor inclination, a dual axis inclinometer with a measuring range of ± 30°, a sensitivity of 1638 counts/g is used. The digital absolute barometric pressure sensor has a resolution of 1.5 Pa and a measuring range of ± 50 Pa. All sensors have a standard SPI digital interface, an internal temperature device and automatic compensation mode. These three kinds of sensor are mounted on a sensor board in the node. Besides this sensor node, a second type node with precise position sensors is used for elongation-measurements (Fig. 4). Two different types can be integrated into the network as potentiometric displacement transducers and linear magnetorestrictive position transducers. They are used to monitor the opening and closing of cracks and fissures according to classical extensometers. The measuring range of the displacement transducer used has a length of up to 1 m with a given linearity of ± 0.05 % of the effective range. The magnetorestrictive
transducer used in this project has a measuring range of 1000 mm, with a given linearity of < ±0.01 % of the effective range.

To prove the quality of the sensors integrated in the system in laboratory, tests under stable and dynamic conditions were conducted to obtain information about data spreading the accuracy of the different sensors in the setup. The analyses showed that all sensors show very small data variations without measurable data drifts. For example the tilt sensor showed about +/- 0.06° (Fig. 4), the acceleration sensor showed an accuracy of +/- 0.008g, and the accuracy of +/- 0.1 mm is achievable in the displacement transducer. Under dynamic conditions, there is a change of >0.1° for the tilt sensor, of >0.02g for the acceleration sensor, and of up to 0.1 mm for the elongation sensor.

Fig. 5. Tilt sensors (which are also acceleration sensors) in the department lab identified construction work at the departments building over 3 floors distance

Fig. 5 shows the performance of the WSN when monitoring the ground motions. A sensor mounted on the roof of a building to monitor vibrations over a distance of 3 floors due to construction work near this building. As these sources emit comparably small energy in the solid concrete frame building, accelerations of relevant magnitudes for seismic landslide initiation (>4 according to Keefer, 1984) will be recognized by the system easily.

Further field test was performed in 2009. A small wireless sensor network with 7 nodes and one gateway was set up on the landslide Super Sauze in the south of France for one week in summer 2009 (Fig. 6). This landslide is located in weathered soft clay shales and is still very active since its initiation in the 1960’s. Even though the measuring period was very short, and some small movements in the area have been observed during the measuring. According to the displacement transducers, crack opening of 1.5 mm in 5 days have been observed and later validated with data from a nanoseismic array. The test showed that the system can be used also in slow moving landslide environments. Also the installation of the system in the previously unknown environment was easy and fast. First data have already been obtained shortly after start up.
Since autumn 2009 the system was tested in the “Elbsandstein” mountains in Germany to monitor joint opening in rock pillars to prove the long-time stability and remote data transfer under real conditions.

4. Wireless sensor networks in seismic landslide hazard management

For the past two decades a large number of landslide warning systems have been developed and applied for general public and industrial purposes. Especially in industrial countries near alpine mountains, the landslide warning systems reach a considerably high standard. Anyhow these systems are usually monolithic, not flexible and adaptable to other situations, expensive and afford time consuming installation and maintenance work. The issue of earthquake triggered landslide warning and monitoring was initiated at least by the Chi-Chi earthquake in 1999 and more recently by the Wenchuan earthquake in 2008. Anyhow there are very little observable advances in earthquake early warning. Most of advances are related to lifeline protection and earthquake monitoring but not landslides. The SLEWS (Fig. 7) with simple inexpensive and flexible monitoring devices in a wireless sensor network provides some advantages and options for the application in the field of surface deformation and landslide monitoring in a seismic environment. The described configuration with acceleration sensors allows also a monitoring of local ground accelerations exceeding relevant ground acceleration.
The monitoring systems based on cable less network connection and data routing ad WSN improves the operative integrity of the system in an event case. The larger landslide events related to earthquakes usually lead also to large surface movements which can destroy cable connections of conventional monitoring systems. Here the ad-hoc reorganization of the WSN allows a self healing of the network, even though some of the sensor nodes might fail or be destroyed in an event case. The only limit of this system is that, the operational sensor density is related to the maximum range of stable data transmission between single nodes in the multi-hop mode. Not only data routing inside the network can be arranged cable less, but also the data uplink to the central data infrastructures for hazard monitoring and management can be arranged cable less by 3G or satellite connections.

A second advantage of SLEWS is the easy installation and start up in the field. The sensors just have to be placed at points or situations in the field where have to be monitored. After switch on and initialization, the nodes automatically connect to the gateway or neighboring nodes. Even though in larger setups, only 10 minutes are needed for the nodes to operate in the network and transmit sensor data through the network after installation. The gateway, where the internet and server connections have to be established and tested, is also easy to be setup. This means that the system can also be used as a mobile component for relief operations to monitor, e.g. endangered road cuts, slopes or landslide dams. After completion of the operation the system can also be easily dismounted and used for new tasks.

Besides these operational aspects, there is a general need to derive on-site acceleration data after a seismic event in landslide environments. Due to the integration of precise but cheap MEMS technology accelerometers, it becomes affordable to derive much more spatial distributed acceleration data. Furthermore the acceleration data from the sensors can be provided in real-time through standardized interfaces for other applications like shake or alert maps.

There is a strong need for further research after the ground failures and landslides related to earthquakes. Earthquake triggered landslides are thoroughly studied and described by Keefer (1984, 2002). The most common method to investigate the landslide susceptibility on a regional or sub-regional scale is the deterministic approach based on the Newmark’s sliding
rigid-block model (e.g. Jibson et al., 2000). As ground acceleration is one input data which are usually predicted based on potential events. Therefore, a broader application of sensor networks might provide more accurate data in the future. Furthermore additional data will help to calibrate these methods for different environments, improve them and develop new approaches. There are only few on-site or close to site acceleration data available for seismically triggered landslides. Contrary to the assumptions of the Newmark model, recent research indicates that besides horizontal acceleration/shaking also vertical acceleration/shaking might have a relevant impact on slope stability in some situation (Aoi et al., 2008; Tang et. al., 2009). Additionally there is a considerable need for research regarding site effects and amplification in highly structured topographic environments.

5. Modeling and sensor data

To build the landslide warning system, the slope stability analysis is necessary. Methods for determining the slope stability under seismic loads have grown steadily since the beginning of last century. The first approach for modeling the earthquake effects is Terzaghi (1950) formulated the famous pseudo-static analysis, which is a static limit equilibrium analysis based on an additional seismic force. This method does not account the constitutive relationship of soil. As a result, there is only one safety factor of slope without the process of failure. In addition, a kind of stress-strain method was developed and applied to banks (Clough and Chopra, 1966). Today, in addition to the static analysis, the numerical simulation also allows a dynamic analysis such as slope stability during seismic excitation. It is a more rigorous method which can simulate the earthquake effect on the slope very exactly, and fewer assumptions about the boundary conditions are possible.

The main difficulty for numerical modeling is to determine the geotechnical parameters used in material law. The usual means of determination is laboratory and in situ experiments, or the use of empirical classification systems in rock. The results of all methods are fraught with uncertainties due to uncertainty factors such as heterogeneity, representative experimental conditions, etc. To reduce these uncertainties, the inverse analysis can be used to improve the numerical modeling.

Inverse methods are divided into analytical approaches, numerical simulation- such as FEM, FDM and BEM, etc. Here, the equations describing the system behavior can be inverted in the manner that the material parameters as a result and the measured quantities occur as input. Figure 9 shows a schematic of the inversion method, which takes advantage of the back-analysis.

![Fig. 9. Scheme of the observational method using back analysis in the process](image-url)
The measured data to validate or update the input values (such as the geomechanical parameters) using models based on the numerical simulation. An example of a homogeneous embankment under earthquake loading will be shown in follows, and the application of real-time measurements to improve the modeling by means of inversion. The numerical simulation is performed with the software FLAC.

Figure 10 shows the selected example with 25° slope angle, length of 200 m, left height of 35 m, and right height of 80 m. The initial input soil parameters are listed in Table 1 (dilation is disregarded).

Table 1 the soil parameters

<table>
<thead>
<tr>
<th>Density (kg/m³)</th>
<th>Bulk (Pa)</th>
<th>Shear (Pa)</th>
<th>Cohesion (Pa)</th>
<th>Friction angle</th>
<th>Dilation (°)</th>
<th>Tension (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>5.1e8</td>
<td>2.3e8</td>
<td>2.5e4</td>
<td>25</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Fig. 10. Finite difference mesh of the slope

As a seismic load, the Loma Prieta quake California (1987) applied (left abutment of the dam Lexington) with a maximum acceleration of about 2.7 m/s² (0.28 g) and a duration of 40 seconds (Fig. 11). A fast Fourier transform acceleration of analyses recording results in a response spectrum (Fig. 12).

In the dynamic analyses, the free-field limit as both sides of the model. The filtered acceleration is set at the base, which in turn is modeled in the model as immobile in the y-direction (bedrock). It is the Mohr-Coulomb failure criterion used and the recording of the deformation gradient calculated at the locations of sensors for real-time evaluation.

Fig. 13 shows a relative displacement of one point of the sliding mass by numerical simulation. The solution is converged to a certain displacement, and it means this is a stable slope.
In the following step, the geotechnical slope parameters are modified by inversion based on the comparison of displacement history of the numerical simulation and real-time monitoring, until the results from monitoring and numerical simulation are very close.

At last, the developed numerical model can used to analyze a deformation development in a long time or due to a higher-magnitude earthquake, helping to improve the warning system.

6. Conclusions

Besides precipitation triggered landslides, a major thread from landslides is related to earthquake which account for the majority trigger for landslides. Furthermore in the case of large earthquakes not only the risks and damages from the landslides themselves, but also cascading effects as consequence of the initial landslide like reservoir or landslide dam failure may cause even larger losses. Due to the rising vulnerability of the society to natural hazards like earthquakes and landslides, the requirements for early warning and monitoring systems continuously grow. Especially reliable real-time data for the detection of hazards, fast warning and quick response are of special relevance to protect humans and infrastructure in the course of hazard management. Although, the environments in which these systems have to operate are often inhospitable for the technology, and by far no ideal systems can cope with these difficulties. Therefore it is reasonable to use robust but also self-sustaining instruments that can operate before, during and after the event.

The Sensor based Landslide Early Warning System-SLEWS described here uses a wireless ad-hoc multi-hop sensor network to monitor landslide processes and the surface deformations. Different kinds of low-cost micro-sensors (MEMS) are integrated in the system to detect different kinds of movements like tilting, acceleration or spreading. Due to the fast data transfer, processing and visualization process, monitoring and also warning in real-time becomes possible. The combinations of different sensor data (sensor fusion) allow to cross-check and evaluate the sensor signals according to decision theory. This contributes essentially to the enhancement of data quality but also to the reduction of false alarm rates. Application of interfaces according to the sensor web enablement OGC guidelines allow to easy set up web based modular monitoring or early warning structures and to integrate the system in existing spatial data infrastructures. Finally wireless self organizing sensor networks can be setup very easy with a cost efficient solution.

From a technical and scientific point of view, it is desirable to achieve a higher spatial
availability of ground acceleration data in mass movements, particularly in future by the operation of a large number of sensors and sensor networks. The real-time availability of these data could also help ground acceleration maps and damage distributions to predict or to evaluate fast.

Based on the real-time monitoring data, the geotechnical parameters can be accessed via the back-analyses to improve the accuracy of the numerical modeling, and make the warning system more practical.

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Reference

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