Earthquake-triggered landslides in Switzerland: from historical observations to the actual hazard

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ABSTRACT

The building inventory in the Alpine area multiplied over the last century, increasing exposure to potential earthquake impacts. This is particularly critical in relation to earthquake-triggered mass movements. In Switzerland, it is possible to assess the spatial extent and impact of such secondary earthquake effects from historical and paleo-seismological analysis of past damaging earthquakes. After calibration against observations of these events, scenario modelling has been recently implemented within ShakeMap, a tool applicable to near real-time estimates. The spatial resolution could be improved using additional information like rock-slope hazard maps or detailed studies on particular unstable slopes. In order to improve our understanding of the dynamic response of unstable rock slopes, an extensive measurement campaign is presently being performed to determine eigenfrequencies, ground-motion polarization and amplification features, and to estimate the volume of the instability. A semi-permanent seismic installation was set up at the Alpe di Roscioro (Preonzo) site, a slope that is close to collapse, to continuously monitor seasonal variations of its dynamic behavior and how it changes over time.

KEYWORDS

earthquakes; induced phenomena; landslides; rock fall; tsunamis

INTRODUCTION

Moderate to high seismic risk in Switzerland results from moderate seismicity combined with high population density, high degree of industrialization and relatively low preparedness level due to the comparatively high return periods of damaging events. 28 events of moment magnitude $M_w \geq 5.5$ have been identified over the past 700 years, twelve of which caused severe damage (Intensity of VIII or higher). The epicentral areas of the strongest events experienced extensive damage from the earthquake ground motion and different induced phenomena. Such phenomena are liquefaction in the river plains, reactivation of landslides, extended rock-fall and tsunamis in lakes generated by induced mass movements. Nevertheless, we expect that smaller but more frequent earthquakes may induce large ground motions locally, as well as small-scale movements and failures of critically stressed slopes.

Due to engineering progress in the last two centuries, seismically unfavorable sites have become attractive for the establishment of settlements and industries. Many villages have

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expanded into the river plains and reached the toes of hazardous slopes in the valleys. Future earthquakes will therefore cause more damage than in the past. Focused studies might therefore help to identify areas at risk and to develop strategies for the mitigation of possible impacts.

EARTHQUAKE INDUCED EFFECTS DURING PAST EVENTS IN SWITZERLAND

Several events with significant induced effects have been reassessed in the course of the historical revision of the Earthquake Catalogue of Switzerland ECOS-09 (Fäh et al., 2011). A wide variety of historical documents, e.g. chronicles, administration documents, newspaper articles, diaries and scientific articles, describing such effects have been found and analyzed (e.g. Fritsche et al., 2012). Events with significant induced effects are the ones of 1584 at Aigle Mw=5.9 (tsunami and landslides), 1601 in Obwalden Mw=5.9 (landslides and tsunami), 1755 at Brig Mw=5.7 (landslides), 1855 at Visp Mw=6.2 (liquefaction and landslides), and 1946 at Sierre Mw=5.8 (liquefaction, landslides, and avalanches).

The main shock of the 1584 earthquake series at Aigle on March 11 had an epicentral intensity of VIII. It triggered subaquatic slope failures resulting in a small tsunami and seiche in Lake Geneva. The strongest of the aftershocks triggered a destructive rock-fall covering the villages Corbeyrier and Yvorne, VD, killing about 320 people (e.g. Fritsche et al., 2012). The earthquake of 1601 in Unterwalden produced several rock-falls in central Switzerland. The rock-fall at mount Bürgenstock collapsed into the lake and earthquake-triggered subaquatic landslides produced a high wave and a seiche in Lake Lucerne causing heavy destruction in the proximity of the shorelines (e.g. Schwarz-Zanetti and Fäh, 2011). The historical accounts on the destructive wave could be complemented with sedimentological studies that indicated a number of similar events in the past 15,000 years (e.g. Strasser et al., 2013). Among the relatively rare reports on earthquake-induced effects of the 1755 Brig event are an earth slump near Brig and accounts about fissures and cracks in the ground that can be interpreted as evidences for liquefaction. The event probably also triggered a large rockslide with an approximate volume of 1.5 million m^3 destroying parts of the village of Niedergrächen (Gisler and Fäh, 2011; Fritsche et al., 2012). A large number of induced effects are documented in the case of the strongest earthquake of the last 300 years in Switzerland, which occurred in 1855 at Visp. Among them are rock-falls and landslides, as well as liquefaction-related ground deformations, lateral spreading and ground settlements (Fritsche et al., 2012). Similar effects are documented for the 1946 earthquake sequence at Sierre (Figure 1). Since the main shock occurred in wintertime, avalanches are also among the documented effects (Fritsche and Fäh, 2009; Fritsche et al., 2012).

Paleo-seismology provides information about severe events that occurred in pre-historic times. The available data is mostly related to potentially earthquake-triggered mass movements in lakes and corresponding induced tsunamis. One of the most significant potentially earthquake-related event is the Tauredunum rock-fall in AD 563, with a destructive tsunami in Lake Geneva. This event is documented in medieval chronicles as well as in the natural archive of lake sediments (e.g. Kremer et al., 2012). Several coeval slope failures occurring around 2200 BP in different Swiss lakes, such as Lake Zurich, Lake Lucerne, Lake Geneva and Lake Neuchâtel suggest another very large seismic event in Switzerland (Strasser et al., 2013; Kremer, 2014; Reusch et al., 2015). Another potentially earthquake-triggered flooding event has been dated in Late Iron Age documented by the destruction of a Celtic wooden bridge in Cornaux, NE (e.g. Grolimund et al., 2015).

While some sedimentary and archaeological evidence in Switzerland could be attributed to historically documented seismic events, it is a more difficult matter for events prior to 1000 AD. To reduce the uncertainties inherent to paleo-seismological events, e.g. due to dating, it is indispensable to integrate all available data. Therefore, the Swiss Seismological Service (SED) is currently collecting the available datasets in a common database with homogeneous quality criteria (Gassner et al., 2015).

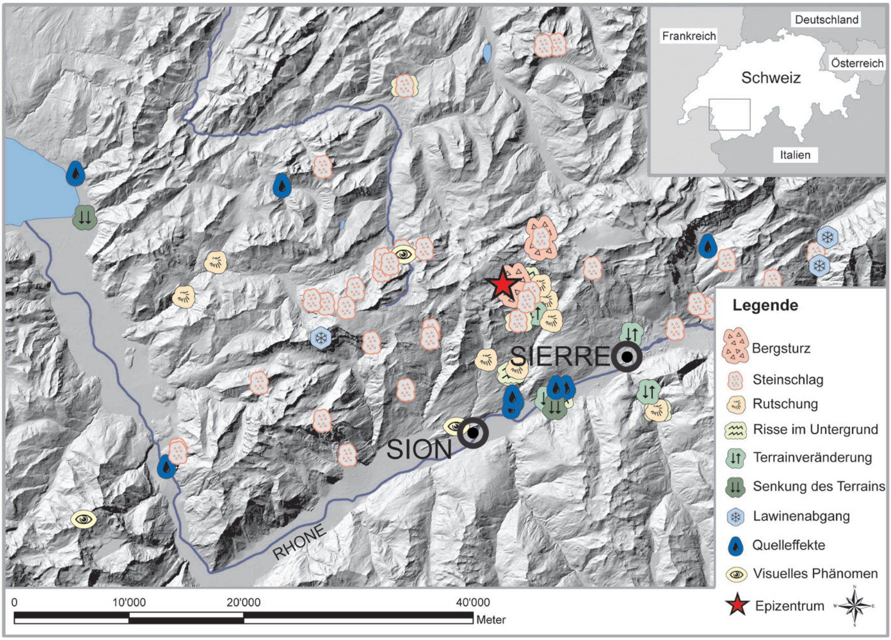

Figure 1: Earthquake-induced effects of the 1946 main shock at Sierre and its largest aftershock (after Fritsche et al., 2009).

EARTHQUAKE-INDUCED EFFECTS IN FUTURE EARTHQUAKES

Quantitative estimates of co-seismic land sliding (distribution patterns, magnitude-frequency relationships) and subsequent impacts are still difficult today. This is due to many input parameters they require. We therefore presently follow two different strategies: investigations on unstable rock slopes to understand their dynamic behaviour, and the development of regional models for earthquake triggering of landslides.

At first, estimating the likelihood of potentially catastrophic landslides requires thorough understanding of the mechanisms driving slope dynamic behaviour. Long-term strength degradation of brittle rock masses is typically related to progressive failure. This is due to the propagation of new fractures through intact rock bridges and shearing along pre-existing discontinuities. A fundamental difficulty lies in experimental quantification of this process and the strength of fractured rock masses in relationship to the driving forces, i.e. the assessment of how close a given slope is to failure. This difficulty has major practical consequences, as the factor of safety of a slope at a given time defines the amplitude of the short-term disturbance required to trigger failure.

A recent study demonstrated a very specific seismic response of unstable rock slopes. This might be considered as their unique signature (Burjanek et al., 2012). In particular, recorded ground motions (earthquakes or ambient vibrations) are highly directional in the unstable part of the rock slope, and significantly amplified with respect to the stable areas. These characteristics allow mapping stable and unstable portions of the rock mass. The predominant directions of ground motion match the past or on-going displacement directions (Burjanek et al., 2010). These effects are strongest at certain frequencies, which were identified as the eigenfrequencies of the unstable rock mass. The relative ground-motion amplifications with respect to the stable part of the slope reach typically peak amplitudes of 7 – 10 (see Figure 2). These effects are presently being assessed in a project supported by ETHZ on a large number of unstable rock slopes in Switzerland. On the one hand, such strong amplification levels and polarized ground motion may directly influence the potential for earthquake-triggered failure. On the other hand, the seismic response adds additional valuable information to the characterization of such unstable rock slopes. This will allow to further reduce the uncertainties related to stability, volume size and hazard assessment.

Semi-permanent installations of seismic stations on unstable sites allow for long-term monitoring of eigenfrequencies and relative amplifications. It has been shown, that the fundamental frequency of the unstable slope could change with the time, and even could be seen as a precursor of the collapse (Levy et al, 2010). Two seismic stations have been recently installed by SED at the Alpe di Roscioro (Preonzo) site, a slope that is close to collapse. The relative amplification is monitored in time and shows seasonal variations (Figure 2). Strong variability is observed in wintertime (especially during freezing-thawing periods), whereas response is stable during summer. Such analyses are necessary for the correct interpretation of the dynamic response of instable slopes.

The second research strategy deals with the use of geospatial proxies and rapid earthquake shaking information through Swiss ShakeMaps (Cauzzi et al., 2014) for the assessment of the

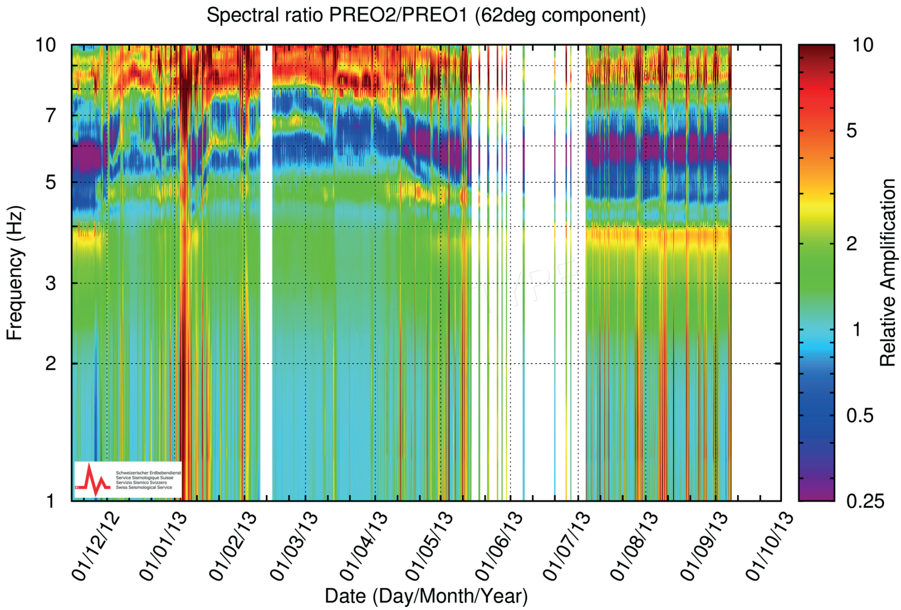

Figure 2: Time variation of the ground-motion amplification (in color) of the rock instability at Alpe di Roscioro (Preonzo, Ticino). Changes in the amplification are due to seasonal variations affecting the global stiffness of the instability in the frequency band 3.7 - 5 Hz, as well as the dynamic response of sub-blocks at frequencies above 7 Hz.

likelihood of landslides, rock-falls and liquefaction in near real-time. Our current prototype implementation relies on the customisation of the global and regional approaches of Nowicki et al. (2014) and Zhu et al. (2015) to Swiss conditions by comparing the predictions with the observations of damaging events. Notable amongst the aforementioned historical earthquakes is the 1946 Sierre event (Mw 5.8) and its strongest aftershock (Mw 5.5) for which observations of the induced effects are abundant (Fritsche and Fäh, 2009). Our best landslide prediction model for the Sierre 1946 event is shown in Figure 3. With a few exceptions, the model can satisfactorily represent the geographic distribution of the observations. The model seems to work better for rock-falls (where just steepness of the slope and ground shaking are the dominating factors) than for soil landslides (where the water content can play a significant role as well). The white diamond close to the epicenter in Figure 3 is the major (4-5 million cubic meters) Rawylhorn rock-fall (e.g. Fritsche and Fäh, 2009). There are large areas in Figure 3, N and SW of the epicenter, where mass movements were not observed. It is not clear if these areas constitute “false positives”. According to Fritsche and Fäh (2009), the secondary effects are well described in contemporary newspaper articles. However, a contemporary damage assessment carried out on behalf of the Canton Valais has survived in fragments implying only partial completeness of the historical dataset. It could be that the dip and state of the rock layers played a significant role in the distribution of the observed mass movements in the area. In general, the distribution of historically known earth-

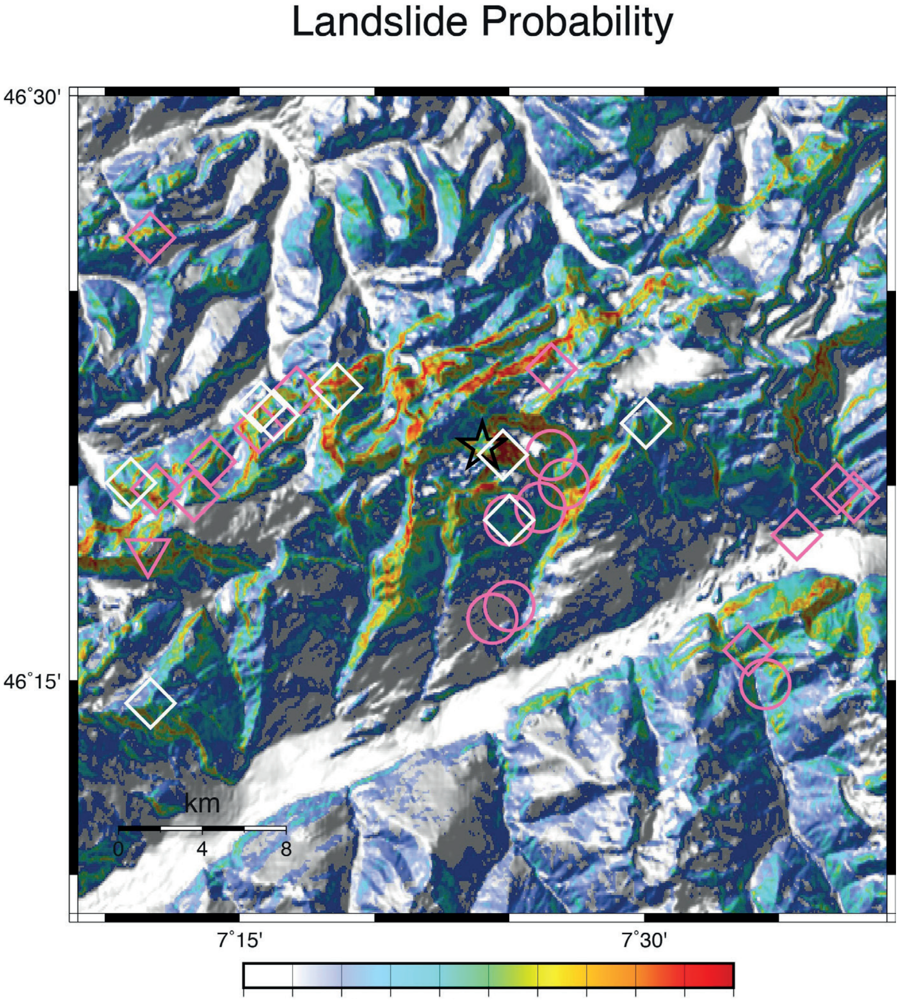

Figure 3: Landslide likelihood scenario for the 1946 Sierre event. The colour on the map from white to red reflects the likelihood from 0 to 1. Symbols indicate the epicentre location (Black star), the observed rock-falls (diamonds), landslides (circles) and avalanches (triangles) triggered by the main shock (pink symbols) and the largest aftershock (white symbols).

quake-triggered mass movements can be modelled satisfactorily. In a further step, cantonal hazard maps for landslide and rock-fall hazards could be included in the procedure to improve the spatial resolution of the prediction model.

CONCLUSIONS

The past earthquakes show impressively, that the Alpine region faces considerable seismic hazard and risk, in particular related to earthquake-induced phenomena such as landslides, rock-fall and liquefaction. Research on earthquake-triggered mass movements is addressed through historical and paleo-seismological analysis of past events, scenario modelling using ShakeMap, and studies of the dynamic response of a large number of unstable rock slopes.
The ongoing research on the micro-vibrations of rock instabilities includes extensive measurement campaign to determine eigenfrequencies, ground-motion polarization features, ground-motion amplification levels, and to estimate the volume of the instabilities. This is resulting in a worldwide unique database of unstable-slope seismic responses. It is an investment for the future. It will serve for the monitoring of potential changes in the unstable rock masses. It is a base for the interpretation of potential future landslides triggered by earthquakes. For example, it could allow quantifying the slope damage after strong shaking (if the slope has not collapsed), and it might be used to improve the ShakeMap approach.
For the ShakeMap approach we presently use georeferenced susceptibility proxies and ground shaking parameters for scenario modelling. However, the primary use of ShakeMaps is rapid estimates of earthquake impacts immediately after an event. This approach is based on accessible explanatory variables combined through simple functional forms with coefficients calibrated against the observations of past events. It is optimized for near real-time estimates based on USGS-style ShakeMaps implemented at SED since 2007.
The presented research has a high practical relevance to Swiss ShakeMap end-users and stakeholders managing lifeline systems. Practitioners and cantonal authorities can run scenarios from which danger zones can be mapped and possible impacts estimated. After a strong earthquake information about possible landslides and rock-fall will be available within minutes. Future improvement might include cantonal hazard maps for landslide and rock-fall. This can be combined with real-time information such as precipitation and temperature, data from deformation devices or seismic stations located on particular instabilities. This research additionally facilitates future investigations on earthquake induced lake tsunamis triggered by subaquatic mass movements.

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