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FROM AMBIENT VIBRATION ASSESSMENT OF POTENTIAL ROCK SLOPE INSTABILITIES TO EARTHQUAKE TRIGGERED ROCKSLIDES

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Abstract

Earthquake-induced landslides have a huge social impact, causing many casualties and significant damage to infrastructure. They belong to the most destructive secondary hazards related to earthquakes. However, the impact of strong seismic events is not limited just to triggering of catastrophic slope failures. It involves also weakening of the internal structure of intact rock masses (and therefore generate new potential rock slope failures) or reactivating of dormant rock slides which remain slow and ductile, but can move in a continuous or intermittent manner over long distances. Hazard mitigation of potentially catastrophic landslides and the assessment of the slope state (i.e., how close a given slope is from failure) requires thorough understanding of the mechanisms driving the slope movements and its seismic response. Our recent studies on seismic ambient vibrations of unstable slopes have shown a close link between the seismic response and the internal structure of unstable rock mass. Thus, systematic passive seismic measurements have been performed in Switzerland during the last two years in order to study the seismic response of potential rock slides concerning a broad class of slope failure mechanisms, material conditions, tectonic settings and activity levels. The data acquisition was conducted with a number of three-component seismometers which were installed at the sites of interest for several hours. During each measurement a reference station was installed on a presumably stable part nearby the instability. Site-to-reference spectral ratios have been calculated to estimate the relative amplification of ground motion at unstable parts. A systematic analysis of the recorded dataset has shown highly directional ground motion in the unstable parts of the slopes and significantly amplified ground motion with respect to the stable areas. These effects are strongest at certain frequencies. The amplification levels at the investigated sites are rather scattered. Amplification factors up to 70 have been observed, which can obviously increase the transient strains during strong ground shaking, i.e. increase the susceptibility of slopes to earthquake-triggering. In most cases the directions of maximum amplification are perpendicular to observed open cracks and in good agreement with the deformation directions obtained by geodetic measurements. Moreover, numerical modelling is performed in order to simulate the seismic waves propagating through the instable rock slope which is represented as a media of different material contrasts, internal fractures and complex topography. The goal of the simulations is to find a model that fits best to the acquired data and therefore improves the understanding of the observed wave field and the key controlling parameters. In addition, the earthquake induced strain transients are also analyzed.

Keywords: seismic ambient vibrations; instable rock slope; earthquake-induced effects; landslide; rock-fall

1. Introduction

Rock slope failures can cause huge damage to society and infrastructure. They can either be triggered by earthquakes or just occur spontaneously due to gravitational forces working on the rock mass. Critical rock instabilities are usually monitored and characterized by displacement measurements. However, such measurements have only limited use in the slope characterization in cases where the rock mass does not move or has stopped moving for a given period of time (i.e, is in a dormant state), but still could collapse catastrophically (e.g., due to an earthquake). We present a technique based on ambient vibrations, which might be a new alternative and supplement to the already existing methods for the slope monitoring and characterization. This technique analyzes the dynamic behavior of the rock mass and adds valuable information about the internal structure of the rock mass. Observations as high amplification and directional ground motion in ambient vibration recordings on instable slopes have already been reported by [1,2,3].

So far the seismic response of 25 different rock slope instabilities has been investigated. Each site delivers quite specific seismic signatures representing the rock-slope properties and hardly allows a direct integration of data from different sites. Geological properties, volume, degree of fracturing, failure mechanism, tectonic settings, the activity level, geometry, etc. are influencing the seismic response of a rock slope. Therefore the goal is to classify the slopes according to their seismic response and try to find links between these classes and the geological (and tectonic) properties.

In this paper we present three sites which have been proposed by Swiss Federal Railways (SBB) see Fig. 1. They have relevance for the railway infrastructure and could cause immense damage in case of failure. The first site is called Dangel in Gurtnellen. At the site Choindez the dynamic behavior of a rock tower is analyzed and the site Axenfluh represents an example of a deep seated instability with a very large volume in the range of around 1 million cubic meters. The volumes of the first two sites are in the range between 1000 to 5000 cubic meters. The detailed measuring configurations of each site are presented in the following together with the results.

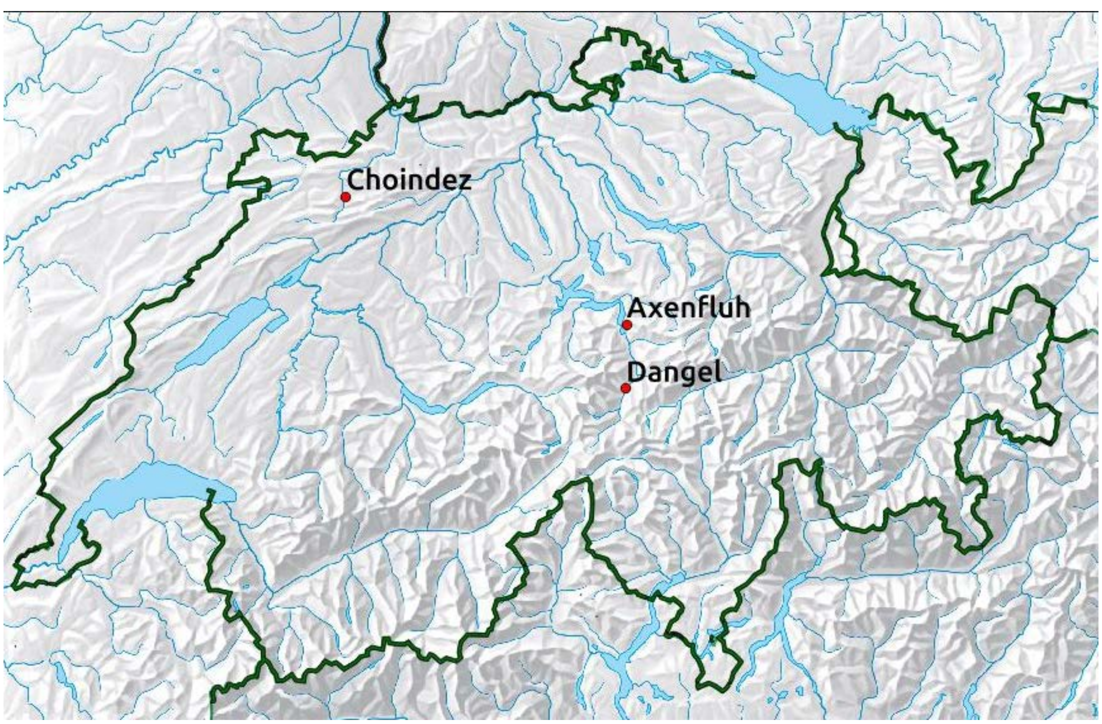

Fig. 1: Overview of the analyzed measuring sites in Switzerland. Base map from [4].

2. Measurement Setup and Methods

The recording time for all measurements was 90 minutes and the data acquisition was done with a digital recording unit coupled to Lennartz 3D sensor. The frequency band of interest lies only up to 20 Hz considering the scales (wavelengths) of interest. At each site two or three sensors were installed: one sensor outside the instability representing the reference station, while the other sensors on the instabilities itself.

The recordings of the seismic ambient vibrations have been analyzed with the time-frequency dependent polarization analysis (TFPA) proposed by [1] and site-to-reference-spectral ratios. TFPA characterizes the movement of the ground particles for each time step and frequency by an ellipse which is described by three parameters, the ellipticity, the strike and the dip (Fig. 2). The ellipticity is the ratio between semi-minor and semi-major axis and describes the shape of the ellipse. A value of 1 means circular, whereas values close to 0 linear movement respectively. Values between 0.3 to 0.4 can be considered as normal or standard for hard rock sites (values observed on average for uncorrelated components of ground motion). The strike gives the orientation of the semi-major axis with respect to North. The dip shows how much the plane of the ellipse is tilted with respect to the horizontal plane. More technical details about the method are described in the paper by [5]. As an example, the output of the polarization analysis for the reference station at the site Dangel is shown in Fig. 2.

The second method is the site-to-reference-spectral ratios (SRSR). In this procedure the recorded time series are split into windows of 100 seconds duration. As a next step, for each time window the Fourier amplitude spectrum is estimated by a multi-taper method [6] and normalized by the corresponding spectrum of the reference station. Then the geometrical mean of all windows is compiled. This procedure can be applied systematically in all horizontal directions. Especially the direction of the main polarization is of interest as maximum amplifications were observed in this direction. The output of the SRSR is a frequency-dependent amplification function with respect to the reference station, which can be used to identify fundamental frequencies of the whole instability as well as other resonance frequencies caused by very local geological features. Very narrow peaks in the spectra (i.e., harmonic signals) are typically interpreted to be caused by anthropogenic sources.

The goal of SRSR is to eliminate source and path specific effects so that only site signatures remain which are related to the instable rock mass. Especially the amplification factor is considered when judging whether a given rock mass is instable or not. For amplification factors around 4 rock slopes are already considered as considerably weakened (and potentially instable), while factor 8 or above represent heavily disturbed rock associated with unstable slopes. Factors up to 70 have been observed in the entire dataset. Such extreme amplifications likely result in a slope failure in case of an earthquake.

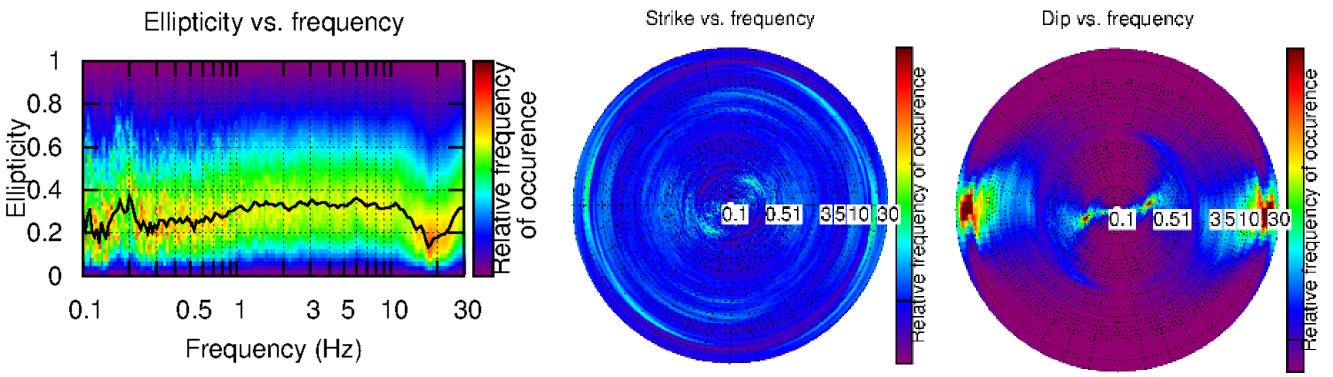

Fig. 2: The three plots are the output from the polarization analysis for the reference station at the site Dangel; the color tells how often a certain frequency occurs in the ambient vibration recording (red=often, purple=seldom); left: ellipticity plot - contains some anthropogenic noise at around 18 Hz; middle: strike plot – north direction goes from the circle center vertically up, there is no polarization for this station; right: dip plot – for around 18 Hz the anthropogenic noise causes horizontal movements as the dip is zero.

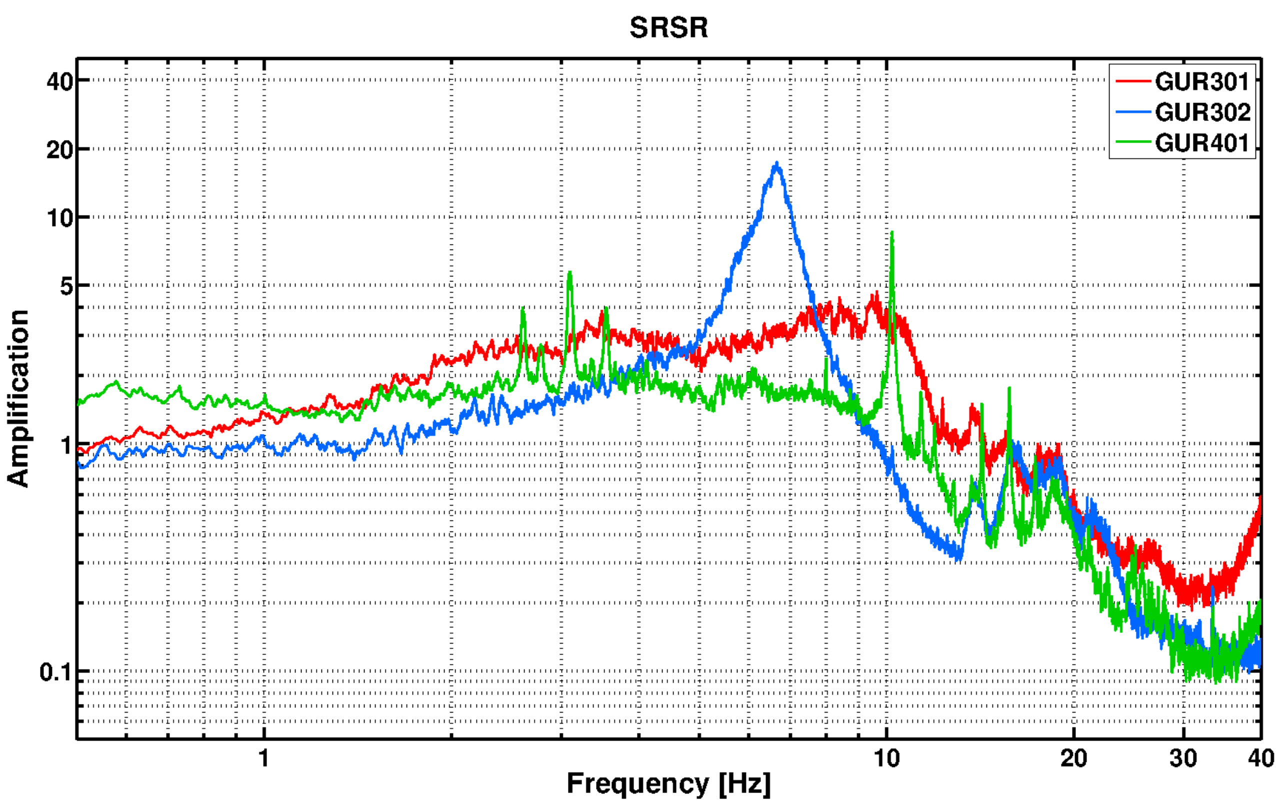

Fig. 3: The Site-to-Reference Spectral Ratios (SRSR) of the site Dangel show the amplitude of the power spectrum with respect to the reference station for each frequency. For the stations GUR301 and GUR302 the SRSR are plotted for the direction of 25 degrees from north and for the station GUR401 for the direction of 35° from north. Very narrow peaks as e.g. the one from the green curve at 10 Hz are interpreted as anthropogenic noise.

2. Results

2.1 Gurtnellen – Dangel site

At this site three points have been measured (Fig. 4), the two exposed points GUR301 and GUR401 and a tilted, massive rock block that is completely cracked on one side. The reference station is located a bit behind the other stations at the beginning of the wood in the background and is not visible in Fig. 4. The SRSR are plotted in Fig. 3.

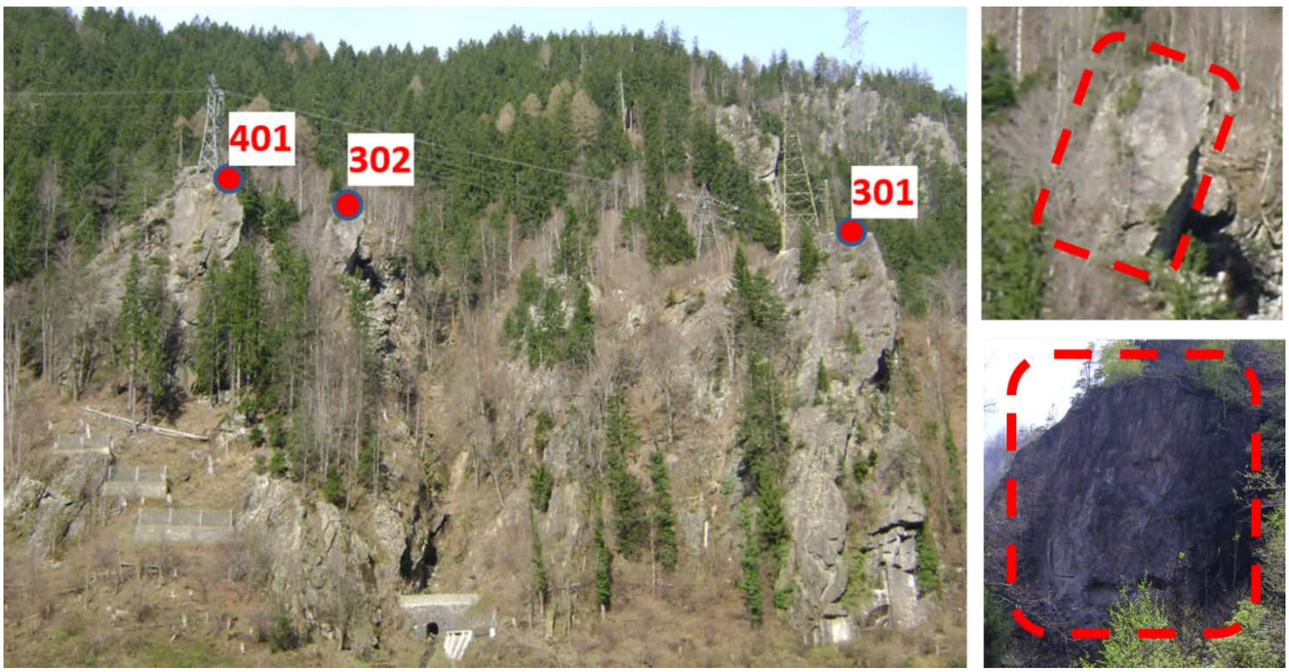

Fig. 4: Left: Overview of the measuring points at the site Dangel at Gurtnellen. The reference station is not visible in the picture as it is installed in the wood behind the three exposed stations (GUR301=301, etc.). Right: Detailed photo of the measuring point GUR302 with view from the east (top) and view from station GUR301 (bottom).

GUR301 seems to be rather stable as the maximum amplification is only about a factor 2-3 between 1-7 Hz, and a factor 3-4 between 7-11Hz. In the 7-11Hz range, the wave field is polarized in the direction 20-30° to the east and shows weak signatures of a dip of 20° with respect to the horizontal. This might indicate that the rock mass is slightly tilted.

GUR302 shows a strong directional and north-south oriented polarization in the ground motion. There is a clear peak visible in the amplification function which can be regarded as the eigenfrequency of the rock block and allows a rather exact estimate of the resonance frequency. The maximum amplification of 16 is reached at a frequency of about 6.6 Hz. The rock mass seems to be internally compact without any major fractures, but detached from the stable base rock. Such clear peaks remind to the seismic response of buildings as the volume is quite well confined and the block swings as one relatively stiff object. For larger volumes with rather fractured internal structure the amplified frequency typically stretches over a certain bandwidth. Due to the dipping of the block GUR302 towards north, we would expect the dip of the polarization analysis different from zero. In fact, we can clearly see a dip angle of 20° at 6-7 Hz for GUR302 (Fig. 5).

GUR401 does not show any significant signatures except one narrow peak at 10 Hz. This peak is slightly damped and most likely caused by the electrical tower next to the station GUR401 which can be seen in Fig. 4. For the whole frequency range of interest the amplification factor lies between 1 and 2, with no polarization of the wave field and also no clear dip signatures. Therefore this part seems to be stable. Considering the fact that station GUR401 has been installed on a quite exposed rock nose, one can conclude that topography alone does not cause strong amplification, respectively polarization. Similar observations have been made by [7].

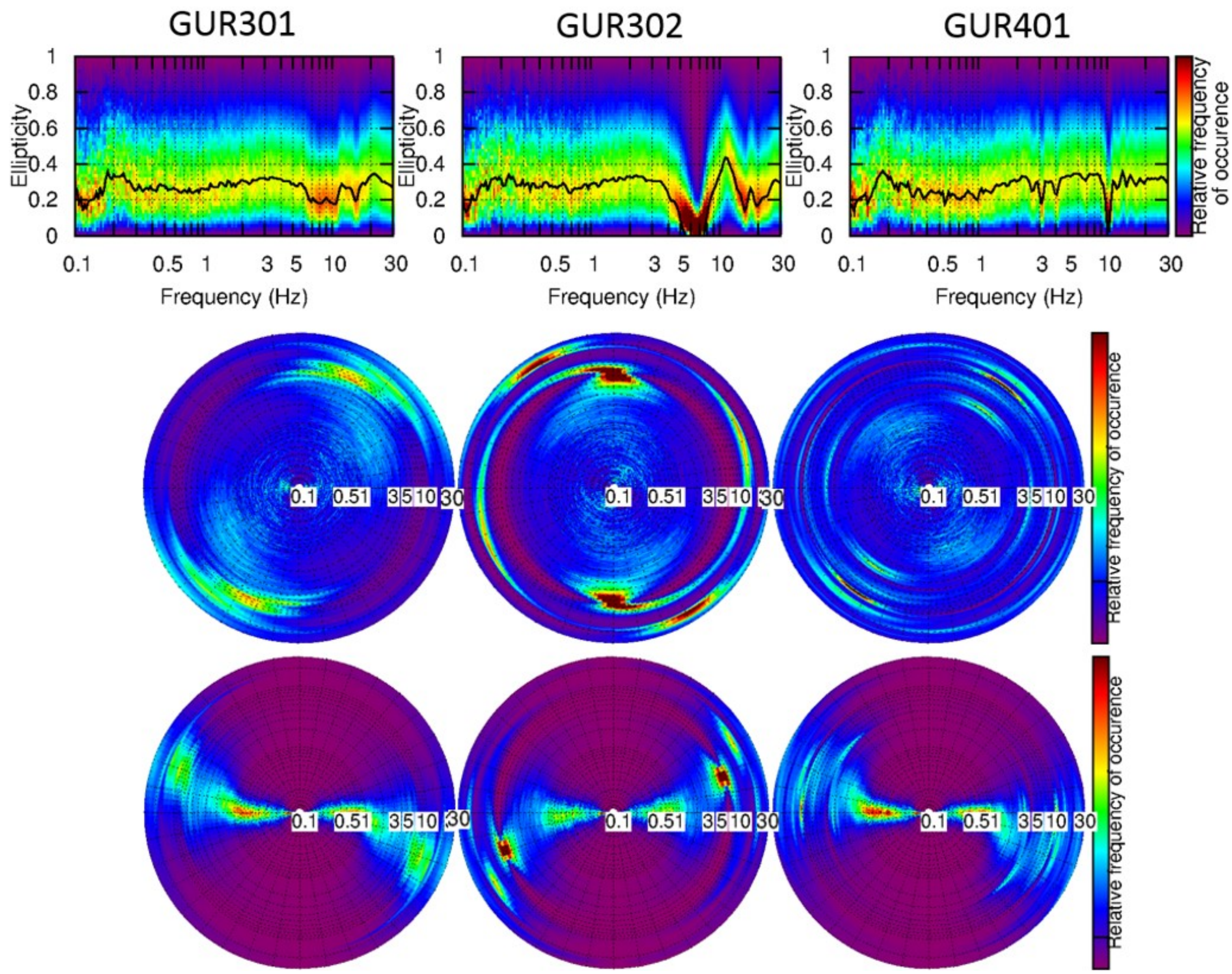

Fig. 5: Polarization analysis for the site Dangel – ellipticity (top row), strike (middle row) and dip (bottom row). The first column contains the results of GUR301, the second of GUR302 and the third of GUR401.

Due to the observed strong amplification, the rock block GUR302 is free to move and might be considered not in a safe state. The ground motion is strongly polarized in north-south direction indicating a potential direction of slow deformation. It is important to notice that this is not the direction where the material would go down in case of a failure. While from the amplification factors point GUR401 seems to be very stable, GUR301 shows polarized amplification of 3-4 in the frequency range 7-11 Hz, which indicates near-surface weakening.

2.2 Choindez – Rock tower site

A rock tower in Choindez is located in the Kanton Jura in the northwest of Switzerland. The tower itself is located right next to the train tracks. The seismic response of the rock column is quite special. The station installed on top of the tower RSJ101 shows a strong directional ground motion for three different frequency bands (Fig. 6). The first frequency band ranges from 5.5 – 7 Hz, the second from 8 – 14 Hz and the third from 18 – 22 Hz. The directional high-frequency part between 18 and 22 Hz shows only an amplification factor of around two. Therefore the focus in the interpretation lies on the two lower frequency bands. Both frequency bands are strongly polarized in perpendicular directions to each other. The 5.5 - 7 Hz frequency band shows an azimuth for the strike of around 110° while the frequencies between 8 and 14 Hz are polarized in direction of 10° to 15° from north. These two frequency bands might represent different eigenmodes of the tower with the specific eigenfrequencies. The dip angle is for all frequencies around zero, indicating no tilt of the tower. The amplified part stretches over one broad frequency band ranging from 5 to 15 Hz (Fig. 7). Between 5 and 7 Hz, two less significant peaks with amplification values of 5 and 10 are recognizable, but the main peak is at 11 Hz with an amplification of 47.

RSJ101 is highly amplified and shows clear signatures in the polarization analysis. Nevertheless it is not clear whether the tower is instable or not as its geometry strongly supports amplification in ground motion and reacts similar to a building for which it is quite common to have high amplification at the eigenfrequencies of each eigenmode.

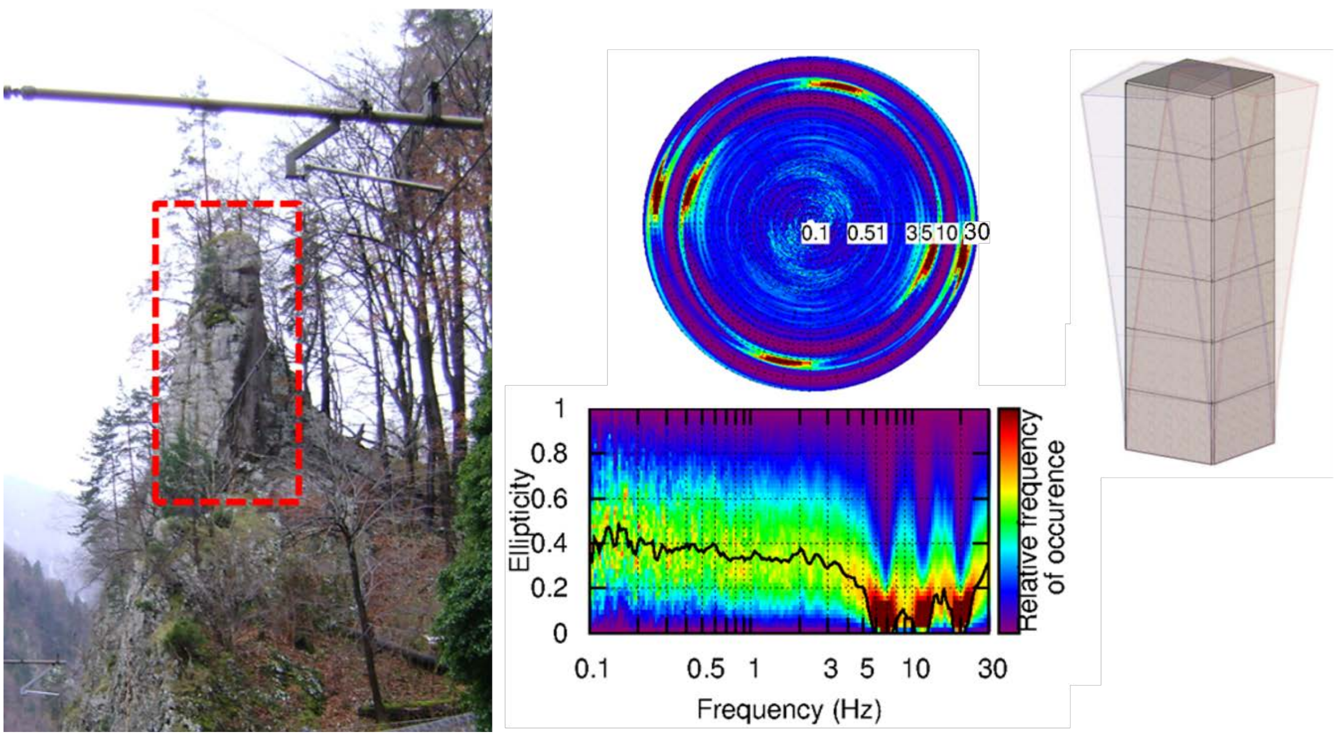

Fig. 6: Left: rock tower in Choindez RSJ101; middle top: strike plot indicating the polarization of the amplified frequency bands which are perpendicular to each other; middle bottom: ellipticity showing the directionality of the ground motion; right: illustration of multi-storey building [8] and its eigenmodes similar to the behavior of a rock tower.

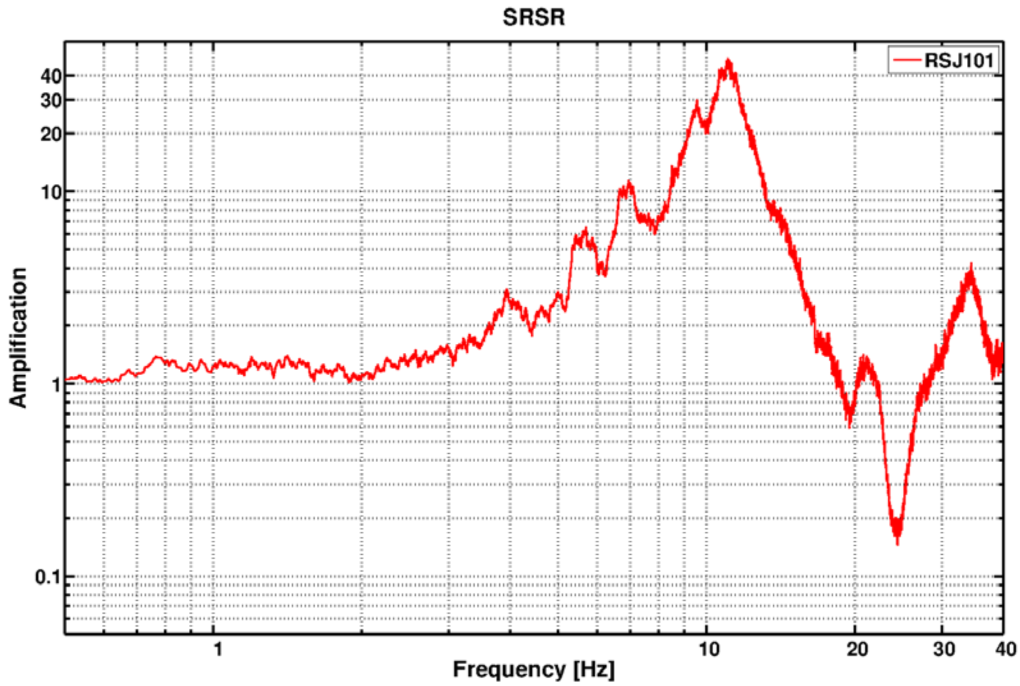

Fig. 7: SRSR of the rock tower in Choindez. Amplification of the ground motion is given in north-south direction with the main peak at 11 Hz, with an amplification factor of 47.

2.3 Axenfluh

According to geological observations the instability at Axenfluh is expected to be deep seated. The lighter spots in the rock wall indicate recent rock outbreaks (Fig. 8, right). Two points were measured at Axenfluh in the area above the lighter spots close to the cliff (Fig. 8, left).

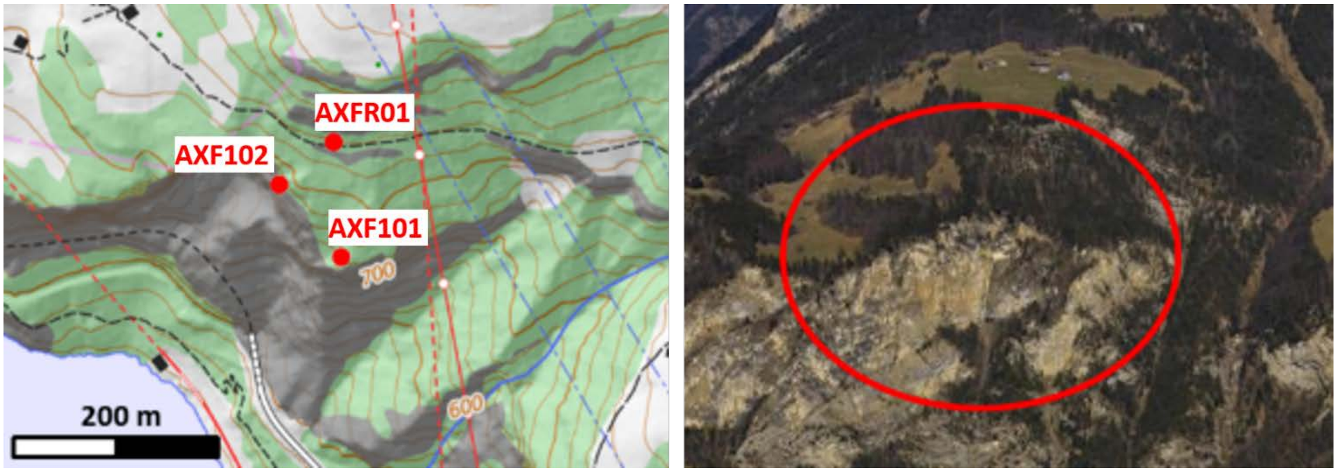

Fig. 8: Overview of the measuring configuration at the site Axenfluh (left) and photo of the site (right).

The results of the two single stations are consistent with each other and the directionality, polarization, dip and amplification look very similar. The amplification factor is between 3 and 7 for the frequency range of 3-12 Hz

(Fig 8.). The observation of amplification down to low frequencies (3 Hz) supports the assumption of a deep seated instability. The polarization is around the north-south direction, with variations for particular frequency ranges at both sites. This observation together with the amplification over a wide frequency band indicate that the instability might be subdivided by deep fractures. The dip observed at the two stations on the instability is 15° indicating that the rock mass might be detached by a tilted cutting plane. A dense network of measurements would allow mapping the extension of the instability.

The amplified eigenfrequencies are stretching over a bandwidth of frequencies with maximum amplifications of around 7. The instability is expected to be deep seated due to the amplification starting in low frequencies around 3 Hz.

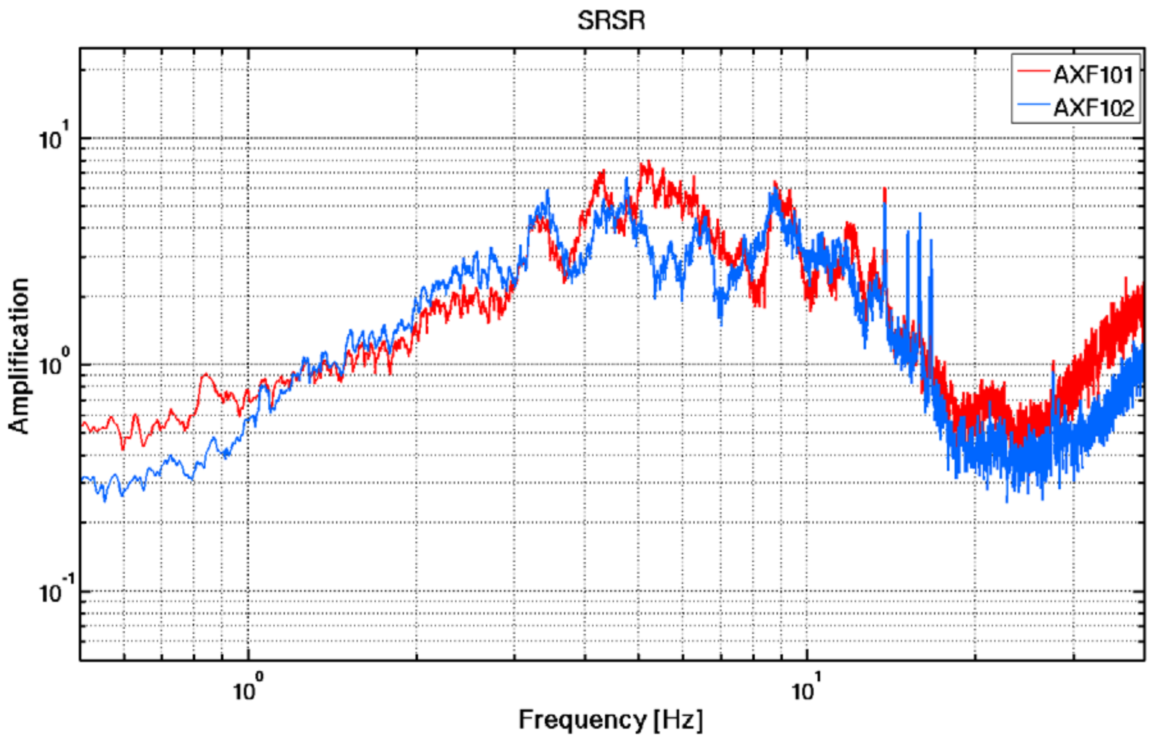

Fig. 9: Site-to-reference-spectral ratios (SRSR) of Axenfluh show the amplitude of the power spectrum with respect to the reference station for each frequency in the north-south direction.

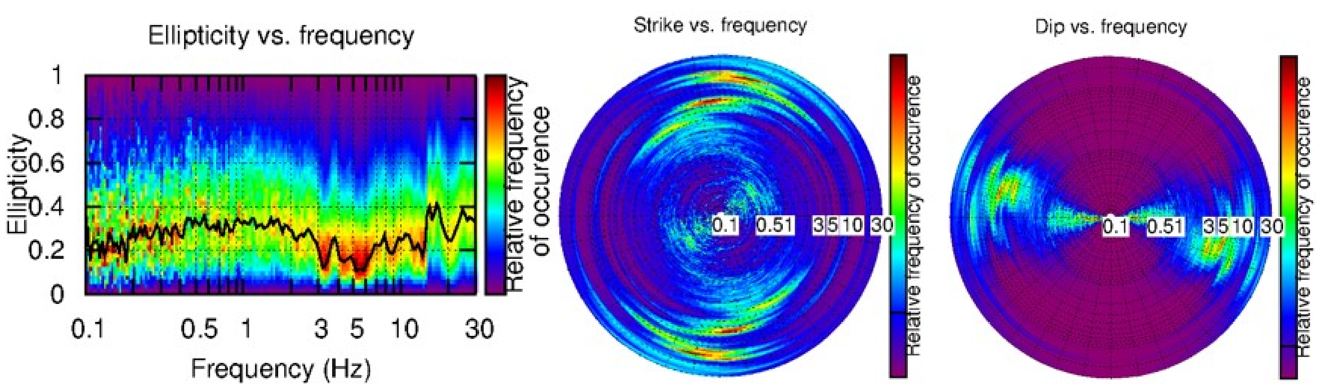

Fig. 10: Results of the polarization analysis for the station AXF101: ellipticity (left); strike (middle); dip (right).

3. Discussion and Conclusions

Even though in the results there are only 3 sites analysed our conclusions are based on the investigation of 25 different sites.

The polarization of the ground motion indicates the direction in which the particles have the highest freedom of movement. If there are open cracks visible at the site, in general the polarization is in perpendicular directions to the cracks. In this context, it is important to notice that the polarization direction is not the direction where the material would go down in case of a failure.

Smaller instable volumes as e.g. the rock block GUR302 at the site Dangel show amplification at higher frequencies at around 6.6 Hz, whereas bigger volumes like the rock slope at Axenfluh show amplifications in low frequencies around 3 Hz. Based on these and several other observations it seems that seismic signatures in the high frequency range represent instabilities with a small volume, amplifications in the low frequency part are rather related to deep seated instabilities.

The amplification factor is one of the main indicators when estimating whether a rock mass is in a critical state or not. In case of isolated rock towers or rock columns like the one in Choindez (or Gurtnellen, site GUR302), one has to be careful, as the geometry plays a major role. The observed resonances might not be linked with the stability in such cases (or in different way with respect to slopes), but just with the geometry. On the other hand, the large amplifications present high susceptibility to earthquake shaking for such structures. In other words, although they do not show slow deformations in long term, they might fail during an earthquake. Since the reference conditions are different from site to site, a direct comparison of the relative amplification factors between the different sites is not straightforward.

Big, complex instabilities are quite often amplified over broader frequency bands as it is more likely that the rock mass contains more faults or fractures than smaller slopes. The more frequencies are amplified the weaker the internal structure of the rock mass.

Earthquakes can increase the transient strains during strong ground shaking which can lead to slope failure or at least a weakening of the rock mass by creating new cracks and fractures [9]. Even if the newly generated fractures and joints are not visible by geological observations, seismic measurements of ambient vibrations can deliver information about the internal structure of the rock mass. It is expected that the spectral amplification will increase significantly after the earthquake.

Furthermore, while looking at the rather exposed station GUR401, it gets obvious that topography alone does not cause high amplifications (except the cases of isolated towers) as the amplification factor is always below 2.5.

5. Acknowledgements

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6. References

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