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Structural and stability analyses of a rock cliff based on digital elevation model: The Obermatt quarry (Switzerland)

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ABSTRACT: The Obermatt quarry is located on the southern flank of the Vitznau sub-bassin of the Lake Lucerne, in the Helvetic Nappes. In the past, the quarry has already experienced major rockfall events involving variable volumes. Due to the difficult access to the slope, a stability analysis has been carried out based on a High Resolution Digital Elevation Model (HRDEM) derived from a terrestrial and airborne laser scanning point cloud. Then, based on the HRDEM, a detailed structural analysis and the identification of the potential failure mechanisms have been performed. Three different failure mechanisms have been emphasized for eight potentially unstable volumes. These volumes have been calculated using the Sloping Local Base Level (SLBL) method and by a geometrical analysis on the laser scanning point clouds. Finally, a safety factor (SF) has been calculated using commercial limit equilibrium codes.

1 INTRODUCTION

The Lake Lucerne is located in the central part of the Switzerland. It is a fjord-type, Perialpine Lake of glacial origin and composed of seven steep-sided sub-bassins (Strasser et al. 2007). Its bedrock is composed from S to N by the Helvetic Nappes, the Subalpine Molasse and the Plateau Molasse which are separated by the Northern Alpine and Subalpine thrusts (Strasser et al. 2007). Previous studies were performed in Lake Lucerne, principally about mass movements, slope stability and deposits during seismic shaking (Schnellmann et al. 2005; Strasser et al. 2007). The quarry of Obermatt is located in the southern slope of the Vitznau sub-bassin, in front of Weggis, in the Bürgenstock-Decke (Fig. 1).

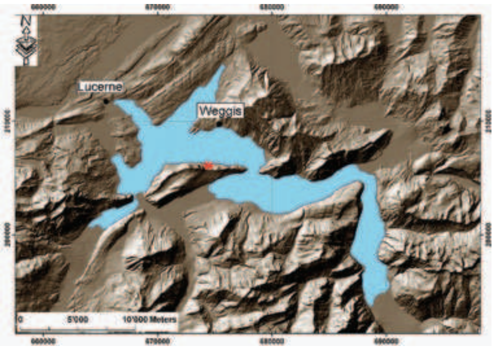

Figure 1. Location of the Obermatt quarry (red star).

The studied area is composed of four lithological units (Fig. 2): the Kieselkalk Formation overlaid by the Altmann member (condensed shale-marly layers), the Drusberg Formation (silty-marly beds alterned with more massive limestone layers) and at the top, Schrattenkalk Formation (massive limestone) (after http://www.stratigraphie.ch/).

In the past, the quarry has already known major events with different intensities. The more recent ones occurred on the 20th June and 20th July 2007 inducing an impulse-wave that reached the opposite shore in Weggis and damaged the beach and some infrastructures (Louis Ingenieurgeologie, 2007). The goal of this study is to present a methodology

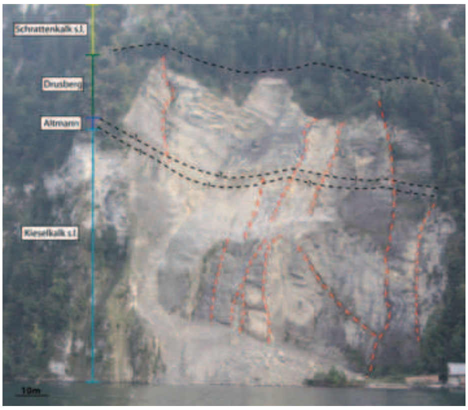

Figure 2. View from the lake of the Obermatt quarry with the main stratigraphy and the major active tectonic faults.

coupling field observations with a more numerical approach in order to assess the stability of potential slope instabilities that threaten to break and fall in the lake.

2 METHODS

A detailed structural analysis has been carried out based on the field observation and on a High Resolution Digital Elevation Model (HRDEM) derived from a terrestrial and airborne (provided by Swissphoto) laser scanning point cloud. The software COLTOP-3D (Jaboyedoff et al. 2007) has been used to determine the orientation of the different discontinuity sets and the result is a colorful point cloud where each color is assigned to a spatial orientation (Fig. 3). When all the discontinuity sets have been identified, the potential failure mechanisms and the kinematic have been tested. (Hoek & Bray, 1981). The potentially unstable volumes have been calculated using two methods: the Sloping Local Base Level (SLBL) method and by a geometrical analysis on the airborne laser scanning point clouds. The SLBL method applied to a 3D surface consists of replacing the altitude z_{ij} of a DEM node by the mean value of the highest and the lowest node altitude among the four direct neighbors, only when the altitude z_{ij} is greater than the mean value (Jaboyedoff et al. 2009). The geometrical method using Polyworks (InnovMetric, 2009) consists in fitting plans along the main discontinuity sets in order to calculate the maximum volumes that could be mobilized. Finally, the limit equilibrium analysis code SWEDGE® was used for a preliminary safety factor (SF) calculation when the instabilities are structurally controlled. When the discontinuity sets are difficult to detect and when the failure mechanism takes place on the intact rock mass following a pseudo circular failure surface, the software SLIDE® was used. Both methods are based on a limit equilibrium analysis assuming a static situation.

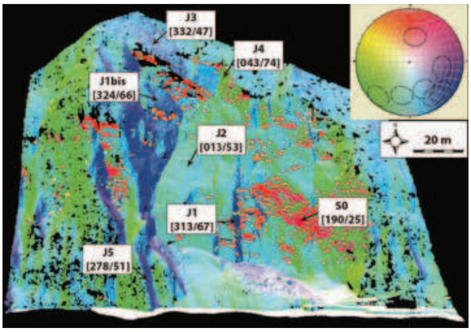

Figure 3. Point cloud of the studied area using COLTOP-3D. Each color corresponds to a dip and dip direction.

3 RESULTS

3.1 *Engineering geology and structural analysis*

The four lithological units composing the cliff have different mechanical properties. The Kieselkalk Formation has persistent (15–20 cm) bedding planes with a very blocky/disturbed structure. The rock mass quality is good to fair (GSI 45–60) (ISRM, 1987). The rock mass quality of the Altmann layer is fair/poor (GSI 30–45) with a weathering degree locally important (Grade II–III) (ISRM, 1987). This is a thin layer (2–3 m) forming the transition between the Kieselkalk Formation and the Drusberg unit. The Drusberg unit is formed by a regular intercalation (10–15 cm) of marly layers with limestones layers. The rock mass quality is fair/poor (GSI 30–45) with an important weathering along marly layers (Grade II–III) (ISRM, 1987). The decimetric to metric bedding planes of the Schrattenkalk Formation have a good rock mass quality (GSI 50–70) that could locally decrease to fair because of tectonic features.

Due to the limited access to the quarry, field structural measurements were performed at the foot of the cliff and four discontinuity sets were indentified (S0, J1, J2 and J4). The presence of slickenslides indicates that J1 is an inverse fault with a pitch of 32°W and is perpendicular to the slope and J2 is fault that is more or less parallel to the slope with a sinistral movement and a pitch of 24°W. With COLTOP-3D (Fig. 3), three more discontinuity sets (J1bis, J3 and J5) have been identified. Their orientations and characterizations are summarized in the Table 1.

Due to the limited accessibility, measurements with the Schmidt hammer and Barton's profilometer have been made at the foot of the cliff only on three discontinuity sets, S0, J1 and J2. The uniaxial compressive strength for the intact rock mass (Kieselkalk

Table 1. Orientation and characterization of the different discontinuity sets observed in the quarry (P = persistence (m), O = opening (mm), S = spacing (cm)).

Name (color, variation)	Dip	Comments
S0 (red-orange)	[190/25]	Bedding planes, P > 10, O = 1, S = 10–30
J1 (dark blue, +/− 8°)	[313/67]	Post-folding tectonic fault, P > 10,O = 1–2, S = 50–150
J1bis (dark blue, +/− 10°)	[324/66]	Post-folding tectonic fault
J2 (light blue, +/− 7°)	[013/53]	Post-folding tectonic fault and/or postglacial reactivation, P = 3–10, S = 1–2, O = 50–200
J3 (light purple, +/− 8°)	[332/47]	Tectonic joint related to folding
J4 (green, +/−14°)	[043/74]	Tectonic joint related to folding, P = 1–3, S = 1–2, O = 30–80
J5 (dark purple, +/−8)	[278/51]	Tectonic joint related to folding

Formation) was estimated between 150 and 200 MPa based on the Schmidt hammer results and manual index tests (ISRM, 1987). The compressive strength of the discontinuities walls varies between 90 and 125 MPa. The value of the small scale roughness has been estimated between 6 and 10 (JRC value) and at intermediate scale, roughness is undulating-smooth. It is important to note that no evidences of sources or seepage are visible on the cliff.

3.2 *Failure mechanisms and volumes estimation*

Based on the observations, the structural setting was compared to the mean topography in order to assess the potential failure mechanisms. Three of them have been identified: planar sliding, wedge sliding and complex mechanism. The kinematic test showed seven possibilities for wedge sliding (Fig. 4a) and that two discontinuity sets (J2 and J3) could lead planar sliding (Fig. 4b).

Eight volumes have been identified (Fig. 5a). Two of them, V1 and V5 are wedges. The instability V1 corresponds to the entire actual crone area of the upper part of the quarry. Its lateral extend limits could be defined by the discontinuity set J1bis for the eastern part and by discontinuity set J2 for the western part with a back–crack surface corresponding probably to the bedding planes (S0). V5 and is a small and well-delimited volume located in the upper part of the cliff with lateral extends limits defined by the discontinuity set J5 for the eastern part and by discontinuity set J4 for the western part. For both V5 and V1 instabilities, SO corresponds to the rear release surface. Their volumes have been calculated using the geometrical analysis method (Fig. 5b) and have been estimated at 290’000 m^3 for V1 and 4’000 m^3 for V5. Four instabilities show a planar sliding failure mechanism. V2 and V2a are comparable in term of shape and maximal stable volume with difference due to the waviness of the discontinuity sets used for the geometrical construction. J1bis and J4 discontinuity sets form the lateral surface for both volumes. The instabilities V6 and V7 are delimited laterally by J1bis and J1 and have smaller volumes than V2 and V2a. All these four instabilities have a basal surface controlled by discontinuity set J2 and their volumes have been calculated by fitting planes following the discontinuity sets delimiting the instability (Fig. 5b). The two last instabilities are more complex mechanisms. The instability VB has eastern limits corresponding to J1, the lower part is delimited by J5, the rear limits are controlled by J2 and the upper back-crack follows the bedding planes. The kinematic analysis indicates that its failure mechanism is planar sliding along J2 in the upper part and wedge sliding (J5ˆJ2) in the lower part. In the eastern part of the quarry, due a low persistence of discontinuity set and a good rock mass condition (GSI 50–70), the geometrical delimitation of the instability B2 is more difficult. The eastern lateral limit corresponds probably to a gully formed by structurally-controlled erosion. The western limit corresponds to the actual cliff under the instability V1 and the upper part is probably close to the limit between the Drusberg and Schrattenkalk formations. Based on the kinematic tests, the failure mechanism is probably a planar sliding along J2 coupled with a rotational multi blocks failure. The volume calculation for this instability has been performed with the SLBL (Fig. 5c). These results are summarized in table 2.

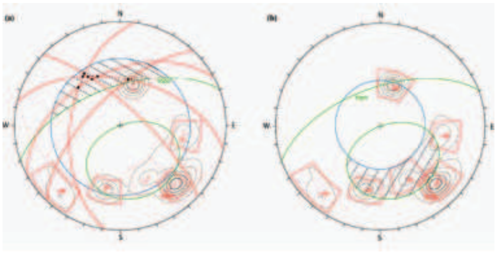

Figure 4. Stereoplot (lower hemisphere) showing the results of the kinematic test for wedge (a) and planar (b) sliding.

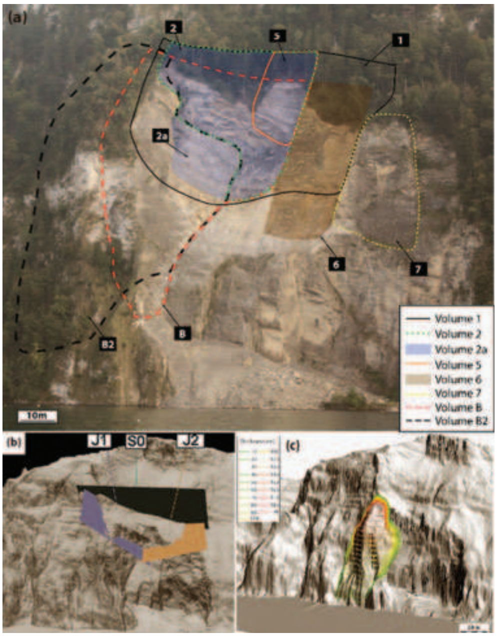

Figure 5. (a) General view of the main potential unstable volumes, (b) example of the geometrical analysis method for the instability V1 and the SLBL for the instability VB1 (c).

Table 2. Characterization of the identified instabilities.

Name	Failure mech.	Disc. Sets	Volume (m^3)	Method
V1	Wedge	J1bisˆJ1	290’000	Geometrical
V2	Planar	J1bis/J4/J2	55’000	Geometrical
V2a	Planar	J1bis/J4/J2	75’000	Geometrical
V5	Wedge	J5ˆJ4	4’000	Geometrical
V6	Planar	J1bis/J1/J2	8’500	Geometrical
V7	Planar	J1bis/J1/J2	7’000	Geometrical
VB	Complex	J5/J2/J1/J4	240’000	Geometrical
VB1	Complex	J1/J2/J5	310’000	SLBL

Table 3. Results of the safety factors (SF) and the probability of failure (PF) for all the instabilities. Both have been calculated with and without the PGA.

Name	SF	SF (PGA)	Relative PF	Relative PF (PGA)
V1	1.6–1.7	1%	1%	10%
V2	1.3–1.4	8%	8%	30%
V2a	1.3–1.4	7%	7%	27%
V5	1.2	24%	24%	62%
V6	1.1–1.2	19%	19%	64%
V7	1.1–1.2	19%	19%	50%
VB/B1	1.6–1.7	–	–	–

In addition of the volumes described before, several small overhanging volumes are present in the upper part of the quarry and indicate that small scale toppling on S0 involving rock traction could also be possible. In the eastern part, an important rock spur is present and complex mechanism like column foot failure or multi-block failure could be present.

3.3 *Safety factor and stability analysis*

The persistence of the discontinuity sets and the rock mass conditions of volumes 1, 2, 2a, 5 and 6 indicate potential structurally controlled failure mechanism. For this reason, a preliminary safety factor calculation (SF) has been made with the software SWEDGE$_{®}$. In order to calculate the SF using SWEDGE$_{®}$, we assumed that the failure took place only along fully persistent fractures. The Barton-Bandis failure criterion was adopted for the calculation and the JRC and JCS used where these obtained with the field data. The stability of volumes VB and VB2 has been assessed with SLIDE$_{®}$ assuming that the failure takes place in the intact rock mass. Concerning the seismic acceleration, previous work has been carried out close to the studied area (Strasser et al. 2007) indicating an influence of seismic shaking on the development of subaqueous slope failure. The influence of the seismic acceleration was introduced in the factor of safety calculation using peak ground acceleration (PGA) for a return period of 500 years. Based on Strasser et al. (2007), the PGA value of 0.12 g has been estimated for Weggis area and introduced in SWEDGE$_{®}$ and SLIDE$_{®}$. Without the PGA, only two volumes (V6 and V7) show a SF close to 1. Except V1, VB and VB1, all the volumes have a SF below or close to 1 when the PGA is taken into account. The results are summarized in the table 3.

4 CONCLUSIONS

This study shows that a numerical analysis combined with a field survey gives a good estimation of the maximal volumes and the structural settings, especially when the access of the studied area is limited. In the case of the Obermatt quarry, the structural analysis based on the HRDEM allowed the identification of three discontinuity sets that were not measured in the field. Using numerical methods, the volume calculation could be evaluated for all the instabilities. Three degrees of susceptibility have been estimated: low (VB, VB2), moderate (V1, V2a) and high (V2, V5, V6, V7). It appears that the most susceptible instabilities are located in the upper part of the slope and present a maximal unstable volume lower than 10’000 m^3. First, geotechnical calculations have been proposed to help the subdivision of the different instability into different susceptibility classes. These calculations show that the influence of external factor like seismic shaking could drastically decrease the safety factor. For this reason, the peak ground acceleration has to be taken into account for the SF calculation especially for all instability because their relative susceptibility could be considerably changed during a seismic loading.

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