USING AVERAGE VELOCITIES OF DEEP-SEATED LANDSLIDES TO DEVELOP INTENSITY-FREQUENCY SCENARIOS

Michel Jaboydedoff, Zar Chi Aye & Marc-Henri Derron
Risk-group - ISTE – Institut des sciences de la terre - GEOPOLIS – 3793 ; University of Lausanne, CH-1015 Lausanne – Suisse
Veronica Artigue & Christian Gerber
DGE - Division GEODE-DN – Section Dangers naturels – Canton de Vaud, Avenue de l'Université 5 - 1014 Lausanne – Suisse
Sébastien Lévy
DGE – Division FORET - Chemin de la Vulliette 4, CH – 1014 Lausanne – Suisse

ABSTRACT
In Switzerland, hazard maps indicate degrees of danger that qualify the potential of events according to their intensity and their return period, usually set at 30, 100 and 300 years. For deep-seated landslides, intensities are determined using average annual displacement velocities. These velocities are in most cases derived from expert opinion based on observations. However, this is not sufficient to establish scenarios associated with the usual return periods. Therefore, we present in this study a method allowing to deduce intensities based on a negative exponential distribution of the landslides' velocities for the three return periods. The intensity scale chosen is the differential movements. The deformation thresholds are a function of the landslide surface and its estimated average velocity. This approach leads to obtain three scenarios serving as data for the risk analysis implemented in a WEBGIS platform. The average displacement velocity (v) and the landslide surface (A) are used to get a differential motion. Based on A and v, the differential strain $\dot{\varepsilon}$ in cm / (m × an) or in % per year is calculated as follow: $\dot{\varepsilon} = 2\,v\,(A/2)^{-0.5}$. It is assumed that the ratio of the length to the landslide width is 2, and that the distribution across the width $\sqrt{A/2}$ is an isosceles triangle. Therefore, $\dot{\varepsilon}$ is a characteristic of each landslide polygon (in a GIS). To define the intensity we assume that a building of width w = 10 m is affected by a deformation during a period of time Δt. The damage degree thresholds (hazard intensities) used for a building are 10, 50 and 100 cm/m. This method applied to the region of les Diablerets (CH) provided encouraging results.

1 INTRODUCTION

In Switzerland, hazard maps were introduced in 1997 (Lateltin, 1997). They indicate the degree of danger that qualifies a potential event based on intensities and their associated return period or frequency. For deep-seated landslides, intensities are determined based on their average annual travel velocities. The estimations of these velocities are in most of the cases based on expert opinion extracted from observations and data analysis. These intensities are not sufficient to establish scenarios associated with return periods, which are in Switzerland set at 30, 100 and 300 years. Therefore, in this study, we present a method which allows to deduce the intensities associated to three return periods using a Poissonian distribution, i.e. negative exponential distribution for the annual average velocities. Here, these intensities correspond to the differential movements potentially induced by the landslides. These values of differential deformation (strain rate) are a function of the surface of the slip and its estimated average velocities. Three thresholds of the intensities are set depending on the potential damage to buildings. This approach provides three scenarios that provide the data for the risk analysis framework proposed in Switzerland (Bründl et al., 2009).

This approach is implemented in a WEBGIS platform (Aye et al., 2016a, 2016b) that automatically calculates risks of objects from a building register, which includes their monetary value and type, and a landslide inventory as polygons with an attribute table containing three intensity classes of velocities assigned to three return periods.

2 MOVING FROM AVERAGE VELOCITY TO PROBABILITY

Based on the average displacement velocity v_0 of a landslide, the probability of exceeding a given speed v must be calculated without further information. For a period of time Δt, the fastest zone of a landslide will move on average by a distance of $L = v_0 \times \Delta t$. Not knowing anything about the distance the landslide will travel during a given time, it can be assumed that the probability that the landslide will move in any interval dx after Δt is given by dx/L. We therefore start from a purely random hypothesis. If P(X≥x) is the probability that the distance traveled by the landslide is greater than or equal to x after Δt, then the probability that the slide is beyond x + dx is (Feynman et al. , 1966):

$$P(X \geq x + dx) = P(x) - P(x)\frac{dx}{L}$$

Knowing that by hypothesis P (x≥X)> P (x> X + dx). This can be equalized to the differential formulation:

$$P(X \geq x) - P(X \geq x)\frac{dx}{L} = P(X \geq x) + \frac{dP(X \geq x)}{dx}dx$$

From where, we obtain:

$$\frac{dP}{P} = -\frac{dx}{L}$$

So that, as P (X≥0) = 1 by definition, the integral is written:

$$P(X \geq x) = e^{-x/L} = e^{-v/v_0}$$

where v is the actual surface velocity during Δt, which means that the slip has traveled x = v Δt, because we have x/L = (vΔt)/(v_0Δt) = v/v_0. Thus the velocity which corresponds to the probability of exceeding it, i.e. P (X> x) is:

$$v = -v_0 \ln(P(X \geq x)) \qquad [1]$$

Figure 1: Schematic view of the effect of a differential movement (blue arrows = velocities) on a building.

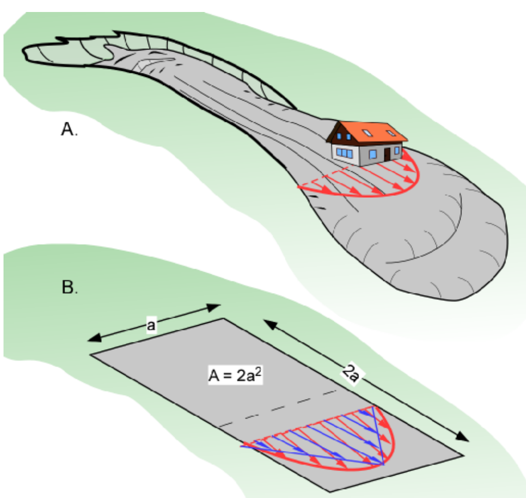

Figure 2: A. Landslide assumed in velocity distribution. B. Idealization of the landslide displacements.

3 FROM THE AVERAGE VELOCITY TO A SIGNIFICANT HAZARD INTENSITY

To go from the average yearly velocity of a landslide to hazard, it is necessary to connect the intensity of the hazard (only known parameter) to a reference object. This is the philosophy of Swiss danger maps. For example, for falling rocks and blocks, the intensity of the hazard is measured by its energy: 30 kJ = resistance of a wooden wall, 100 kJ = concrete wall, etc. (Lateltin et al., 1997). Therefore, which level of the intensity can be considered as high for a building located on a moving ground? Damages occur mainly when there are differential movements within body of the sliding mass or at its limits (Egli 2005, Raetzo and Loup 2016) (Figure 1). Consequently, the average velocity of the displacement (v) relative to the dimensions of the landslides is used. Assuming that the surface of the landslide A is known, the shape of the landslide is idealized by a rectangle with the ratio of the length (2a) to the width (a) of the landslide is 2 (Figure 2). The relationship between the surface A and a is given by the square root of (A/2). The velocity distribution across the landslide is assumed to be an isosceles triangle (Figure 2), which means that the velocity gradient (strain rate) is given by v/(a/2) = 2 v/a. As a consequence, the differential movement - or rather the differential strain $\dot{\varepsilon}$ in cm / (m × year) or in% per year – can be calculated by stating that the fastest velocity is at the center of the landslide:

$$\dot{\varepsilon} = \frac{2\,v}{\sqrt{A/2}} \qquad [2]$$

This value of $\dot{\varepsilon}$ is the characteristic of each slip (polygon in a GIS). The next step is to set limits for intensities and thus to calibrate the damage. It is assumed that a building of width w = 10 m is affected by a deformation during a period of time Δt. It thus becomes possible to calculate the differential displacement dd on w during this period:

$$dd = w \times \dot{\varepsilon} \times \Delta t \quad [3]$$

With $\dot{\varepsilon}$ deduced from the previous formulas (1 and 2) on the basis of the velocity indicated by the inventory, setting w = 10 m and Δt = 30, 100 and 300 years (Figure 3). The results are classified into four intensity classes (Table 1). Thus, setting probability thresholds, corresponding velocities v_0 are extracted for the return periods 30, 100 and 300 years. In the present case, we proceeded by trial and error, and finally opted for three limits based on our knowledge of the field, the averaged velocities corresponding to $P_{30}(X>x)$ = 36.8%, $P_{100}(X>x)$ = 18.4%, and $P_{300}(X>x)$ = 9.2% were chosen.

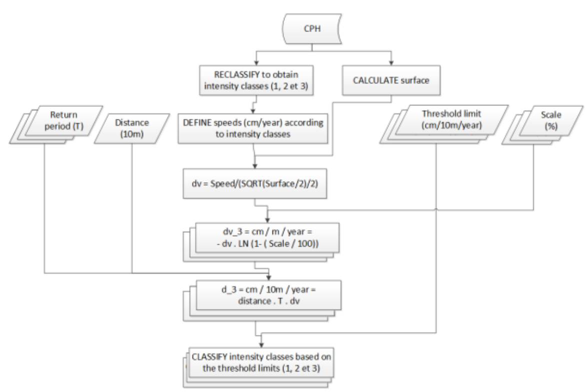

Figure 3: Flowchart of the intensity calculation for three return periods.

Table 1: value of the intensities chosen

Intensity	Thresholds for dd

	[cm / 10 m]
High	I ≥ 100
Medium	50 ≤ I < 100
Low	10 ≤ I <50
Insignificant	I<10

3 EXAMPLES

3.1 Synthetic example

Let us illustrate the calculation for a landslide of a surface of 10'000 m^2 with an average speed of 5 cm/year: $\dot{\varepsilon}$ = v (A/2)$^{0.5}$ = 5 (10^4/2)$^{-0.5}$=0.141. Considering the three return periods, we obtain the results of Table 2 and figure 4. This shows that the calculated displacements for the three return periods reach 42.5 cm, which ranks it in the low intensity for 30 years (Table 1 and Table 2) and high for 100 and 300 years. Inserting in the Swiss double-entry matrix (Lateltin, 1997, Raetzo and Loup, 2016), this makes it possible to locate the three scenarios according to the return period and the resulting intensities (Figure 4).

Table 2: example for v_0 = 5 cm / year, and A = 10000 m^2, with w = 10 m.

Return period Δt [years]	Probability of exceedance thresholds	Corresponding velocity v [cm/an] $v = -v_0 \ln(P(X > x))$	$\dot{\varepsilon}$ [cm m^{-1} an^{-1}] $\dot{\varepsilon} = v\,(A/2)^{0.5}$	dd [cm] $dd = w \times \dot{\varepsilon} \times \Delta t$
30	36.8%	5.0	0.14	42.5
100	18.4%	8.5	0.24	239
300	9.2%	11.9	0.34	1012

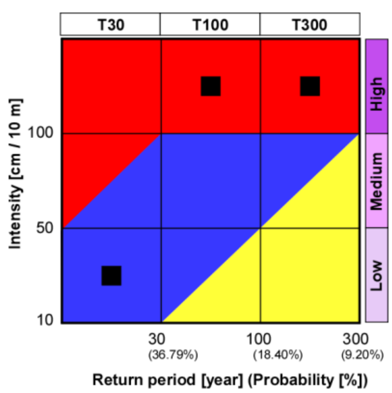

Figure 4: Representation of the data of Table 2 in the Swiss matrix and of the corresponding intensities for deep-seated landslides

3.2 Les Diablerets example

This method has been applied to part of the inventory of the canton of Vaud (VD, 2017) in the Diablerets region. It allows the intensity maps to be established for three different return periods and to assess the total risk of these three scenarios (Figure 5). Compared to the hazard maps based only on velocities (Figure 6), it makes a consistent picture. The active landslides are either in high intensity of 30 years return period or medium for hundreds years (Figures 7 and 8).

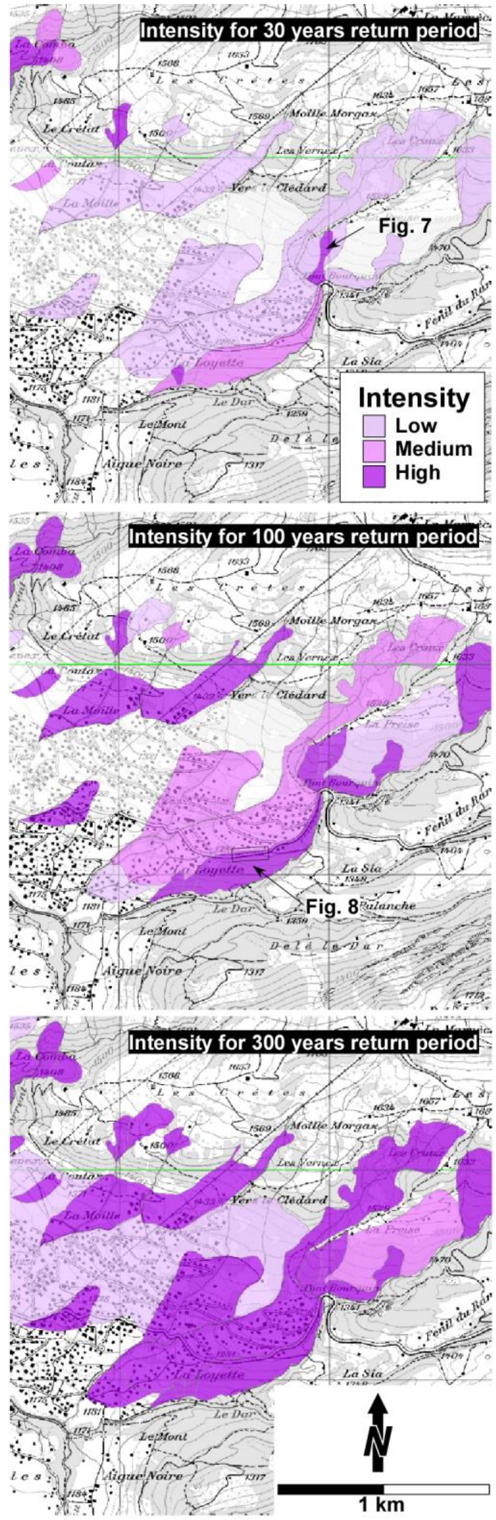

Figure 5: Example of intensity classification according to the proposed method for the 30, 100, 300 years return period for deep-seated landslide (based on VD, 2017).

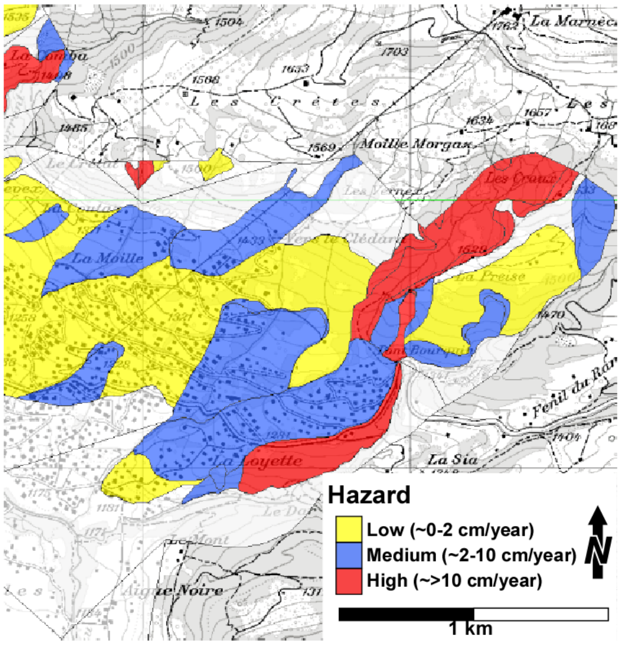

Figure 6: Hazard map corresponding on velocities of the same area of figure 5.


Figure 7: The active landslide of Pont Bouquin (several meters per year), which cut the road located below in 2007 and buried the below river in 2010. The location is visible on figure 5.

Figure 8: Zone of active landslides that strongly deformed the road, which has been stabilized by important work in 2016 (see the white rectangular box). The location is visible on figure 5 (image from map.geo.admin.ch).

It is obvious from the figures 5 and 6 that the red zones are clearly active, but the degree of hazard with the proposed method makes a distinction between them. In particular, it shows that large landslides are potentially less destructive than smaller ones, for equivalent velocities (because the differential movement is smaller). This phenomena is known in the Alps, for instance on the large landslide of La Frasse (about 0.5 m/y but crisis it reached up to several meters a year; Tacher et al., 2005) on which the village of Cergnat slid down over several tens of meters with no massive destruction (Dupraz and and Durussel, 1982). However, one would not recommend building new buildings in this area that can be subjected to a crisis or divided in several compartments of different velocities.

4 DISCUSSIONS AND CONCLUSIONS

This presented method makes it possible to create scenarios that do not exist on the basis of unique information such as the yearly average landslide velocity. This approach considers that the velocity of landslides is a random variable with a known mean. We have observed that by choosing adequate and reasonable thresholds, even though no inventory data is available to calibrate the probabilities, the results obtained are very satisfactory. Calibrating the intensities on the differential motions on an object of 10 m appears to be a relevant solution. The deformation based on the ratio of the average velocity and the square root of the half-surface of the landslide is likely a path of inquiry for the assessment of landslide intensities.

One of the issues is the strong assumption about the velocity distribution across the landslide. To solve this issue an intensity linked to deformation located at the landslide limits must be added. Because, if the landslide moves at its limits by the average velocity, the differential movement will be very large. But in such a case, theoretically, the landslide moves like one block and there exists no differential movements inside the landslide. It shows that another indicator has to be developed for a building at the limit of a landslide.

This method is implemented in a WEBGIS platform, which automatically calculates the risks using the buildings register, including their monetary values and types, and an inventory of landslides as polygons with their average velocities. The first attempt of risk calculations using the three return periods and the corresponding intensities leads to satisfactory results, consistent with our knowledge of the local context.

Finally, this approach implicitly incorporates extreme events, which is relevant from a risk analysis point of view.

5 REFERENCES

Aye, Z.C., Jaboyedoff, M., Derron, M-H., van Westen, C.J., Hussin, H.Y., Ciurean, R.L., Frigerio, S., Pasuto, A. 2016a. An interactive web-GIS tool for risk analysis: a case study in the Fella River Basin, Italy. Nat. Hazards Earth Syst. Sci., 16, 85–101. doi:10.5194/nhess-16-85-2016.

Aye Z. C., Nicolet P., Jaboyedoff M., M.-H. Derron, Gerber C., and Lévy S. 2016b. A prototype web-GIS application for risk analysis of natural hazards in Switzerland. In General Assembly 2016 - V. 18 -4356.

Bründl, M., Romang, H. E., Bischof, N., and Rheinberger, C. M. 2009: The risk concept and its application in natural hazard risk management in Switzerland, Nat. Hazards Earth Syst. Sci., 9, 801– 813, doi:10.5194/nhess-9-801-2009.

Dupraz H. and Durussel R. 1982: Utlisation d'annciens plans cadasraux pour l'évaluation des mouvements de terrain. Vermessung, Photogrammetrie, Kulturtechnik, 80, 345-349. http://doi.org/10.5169/seals-231184

Feynman R, Leighton R, and Sands M. 1966: The Feynman Lectures on Physics. 3 volumes. Library of Congress Catalog Card No. 63-20717.

Lateltin, O. 1997: Prise en compte des dangers dus aux mouvements de terrain dans le cadre des activités de l'aménagement du territoire. Recommandations, OFEFP, 42p.

Raetzo, H. & Loup, B. 2016: Protection contre les dangers dus aux mouvements de terrain : aide à l'exécution concernant la gestion des dangers dus aux glissements de terrain, aux chutes de pierres et aux coulées de boue / auteurs: Hugo Raetzo et Bernard Loup ; traduction: Cristian Marro. Office fédéral de l'environnement OFEV, 98 p.

Tacher L., Bonnard C., Laloui L. and Parriaux A., 2005. Modelling the behaviour of a large landslide with respect to hydrogeological and geomechanical parameter heterogeneity. Landslides, vol. 2, N°1, pp. 3-145.

VD (2017) : http://www.geo.vd.ch/theme/dangers_nat_thm, consulté le 12.05.2017.