Landslide risk mapping for the entire Swiss national road network

L.K.A. Dorren, A. Sandri & H. Raetzo
Landslides, Avalanches and Protection Forest Section, Federal Office for the Environment FOEN, Bern, Switzerland. E-mail: luuk.dorren/hugo.raetzo/arthur.sandri@bafu.admin.ch, Tel. +41-31-3241024

P. Arnold
Federal Roads Office FEDRO, Bern, Switzerland: E-mail: philippe.arnold@astra.admin.ch

ABSTRACT: Swiss-wide, standardized information on natural hazards that threaten national roads (highways) are not available. The Swiss federal roads office (FEDRO) therefore decided to initiate a four year project, aiming at quantifying and mapping all risks due to natural hazards threatening Swiss national roads. Snow and rock avalanches, rock- and ice-fall, flooding, collapse dolines and different types of landslides are accounted for. Landslides include permanent slides, spontaneous slides and shallow debris slides. For all these landslide types the frequency and intensity should be determined by geotechnical bureaus that carry out the field investigations and the subsequent hazard and risk analysis. To aim for a homogeneous and comparable dataset, a methodology for the hazard and risk analysis has been developed. The hazard part of the methodology defines how intensity and probability scenarios should be defined for potential active hazard zones. The risk part defines how the risk of having highway closure, damage to infrastructure or casualties due to landslides affecting the national roads and surroundings should be calculated and visualized. This paper presents the developed method and illustrates how it can be used for calculating the landslide risk on a highway by means of an example case.

1 GENERAL INTRODUCTION

1.1 Context

Natural hazards such as avalanches, rockfall, landslides and flooding persistently threaten Alpine regions (e.g., BUWAL 1999a; Rudolf-Miklau et al. 2006; Bezzola and Hegg 2007). To protect against these hazards, Switzerland invests yearly about 360 million CHF in protective measures, of which 15 million is roughly used for protection against landslides. Not only residential areas, but also highways require protection as shown by recent phenomena such as the rockfall event of June 2006 on the Gotthard highway, the road destructing flooding and landsliding events in August 2005 or the numerous snow avalanches in the winter of 1999.

Since January 2008, the federal roads office (FEDRO) is responsible for the national road network of Switzerland. In many countries this is a normal situation, but in Switzerland, the national roads were managed by Cantonal road services until 2008. As a result, Swiss-wide, standardized information on the type, frequency, intensity and location of natural hazards that threaten national roads, as well as the costs of required protective measures, was not available. The FEDRO therefore decided to initiate a four year project, called “Naturgefahren auf Nationalstrassen” (national hazards on national roads - NHNR) with the technical support of the Federal Office for the Environment (FOEN), aiming at quantifying and mapping all risks due to natural hazards threatening Swiss national road network (total length = 1892 km) analogue to the work of Roberds (2005).

1.2 Project setup

The project methodology forms the basis of the project and describes in detail the following 4 main parts:

1. hazard analysis
2. risk analysis
3. risk evaluation
4. planning of protective measures

As such the methodology defines the natural hazards to be studied, the study perimeter, the standards of the hazard assessment, the risk equations, and values of the prefixed parameters to be used, as well as the products to be delivered. The methodology has been developed by a working group consisting of natural hazard and road management experts from federal and cantonal organizations, universities, and private bureaus. It is mainly based on the methods presented in BUWAL (1999b) and Wilhelm (1999). The methodology does not prescribe models for simulating the different natural hazards to be assessed.

The FEDRO and the FOEN are in charge of the project coordination. The field and modeling studies needed for the hazard and risk analysis are being done by ARGEn (ARGE = *Arbeitsgemeinschaft* = group of jointly working geotechnical bureaus). An ARGE works within a section of the Swiss national road network with a length that roughly varies between 10 and 50 km.

The natural hazards that need to be assessed are snow and rock avalanches, rock- and ice-fall, flooding, collapse dolines and different types of landslides. To aim for a Swiss-wide homogeneous and comparable dataset, 4 event-size scenarios (return period 0 – 10 yrs, 10 – 30 yrs, 30 – 100 yrs, 100 – 300 yrs and intensity classes low, medium and high) should be defined for each the potential hazard source zone. These event-size scenarios are based on the method described in BUWAL (1997). They differ slightly for the landslide analysis method used in this project, as explained in the following chapter.

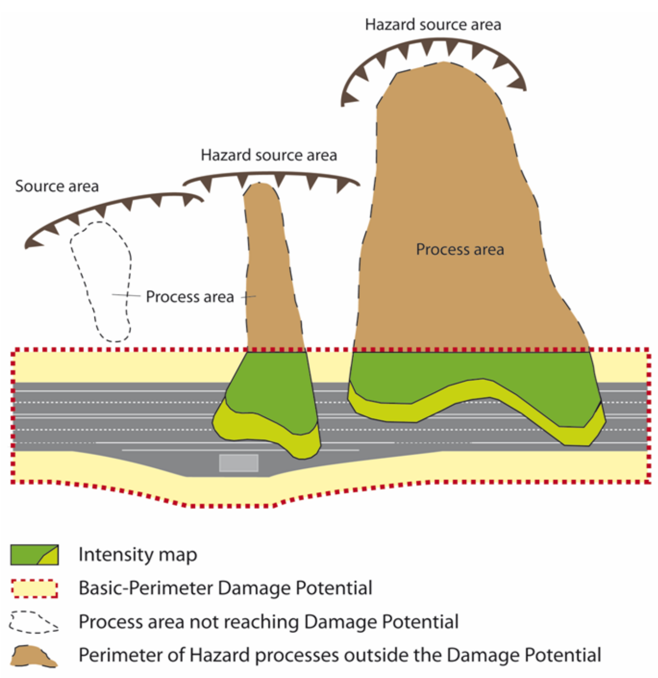

Figure 1. The perimeters defined in the project.

The perimeters that are to be taken into account are defined in Figure 1. It shows that an area of 50 m at both sides of the highway is defined as the damage potential perimeter. All natural hazard processes that reach this perimeter should be studied in detail in the complete area that is covered by that natural hazard, which means from the source to the deposit area. The risk analysis is only carried out within the damage potential perimeter.

2 LANDSLIDE HAZARD MAPPING

2.1 *Probability scenarios*

The landslides part in the methodology developed for the NHNR project is mainly based on the Swiss guidelines on mass movements presented in Raetzo et al. (2002). The landslide types studied in this project include permanent slides, spontaneous slides and shallow debris slides. Permanent landslides are defined as slides that move down slope regularly over long periods. The movements occur along either more or less well formed sliding planes, or existing zones with strong shear deformations. For these slides, the probability of occurrence is equal to 1. A spontaneous slide is defined as a loose rock mass that slides down relatively quickly due to a sudden loss of shear strength under the formation of a slide plane. In spontaneous slides, slide planes are always newly formed, which makes them different from permanent landslides. The occurrence probabilities of the spontaneous slides have to be determined on the basis of historical events, silent witnesses, internal friction, cohesion, pore pressure condition and geometry/topography. Herewith, mainly the mechanisms that lead to sliding acceleration are to be assessed. A shallow debris slide (Hangmure) is defined as a relatively rapid downslope flowing mixture of loose rock material (often mainly soil and vegetation cover) and water. For this type of slides the event-size scenarios for the return periods 30 yrs (0-30), 100 yrs (30-100) and 300 yrs (100-300) should be defined.

2.2 *Landslide intensity maps*

The intensity classes for the three studies landslide types are determined on the basis of the criteria given in Table 1. The area affected by permanent landslides is to be mapped in the field. For the spontaneous slides, this area should be determined on the basis of historical events and comparable values from literature. For the shallow debris slides, the affected area has to be determined using comparable historical events, as well as the energy line angle with a value between 20° and 40° (exceptionally 15°). The NHNR methodology assumes that the maximal runout distance is 100 m in case of a linear slope profile and slide volumes smaller than 1000 m^3. In case of an abrupt transition between the mountain slope and a flat valley bottom, this runout distance decreases to about 20 m, if the slide volume is smaller than 1000 m^3. When estimating the runout distance of these slides, the slope geometry and anthropogenic structures should be taken into account.

The parameters that are finally needed for calculating the landslide risk are the intensity classes and the occurrence probability for all landslide types, as well as the deposit height for spontaneous and shallow debris slides.

Table 1. Criteria for determining the intensity of landslides.

Process	Intensity: Low	Medium	High
Slide	v < 2 cm/yr	v: dm/yr	v > dm/day, or: displacement > 1 m/event
Debris flow	e < 0.5 m	0.5 m < e < 2 m	e > 2 m
	--	h < 1 m	h > 1 m

v = mean annual velocity of slide
E = kinetic energy
e = thickness of the unstable layer
h = thickness of debris deposit

Another important variable is the spatial occurrence probability (Pso). This probability defines the chance that damage occurs within a given area and is calculated as the ratio between the actual affected area and the potential affected area (for further details see BUWAL 1999b). This value should be calculated at the scale of a single slide. Table 2 presents the spatial occurrence probabilities for the three studied landslide types differentiated between the source and transit zone and the deposit zone.

Table 2. Spatial occurrence probabilities (Pso) for the three studied landslides types.

Landslide type	Source / Transit zone	Deposit zone
Spontaneous slide	0.5 – 1.0	0.3 – 1.0
Permanent landslide	1.0	1.0
Shallow debris slide	width of the actual deposit [m] / width of the potential deposit area [m] as estimated by the expert	

3 LANDSLIDE RISK ANALYSIS

3.1 Damage types

The "damage" types considered in this project are highway closure, damage to infrastructure or casualties due to landslides affecting the national roads and surroundings (rest area facilities and gas stations).

Highway closure can occur after a landslide event took place or before the occurrence of a landslide event as a preventive measure. Both damage types are included in the risk calculation. The outcomes of this risk calculation are the costs of highway closure attributed to section of the national road network. Eventually all risk calculations result in costs per highway section due to damage caused by landslides and other natural hazards. The types of damages to infrastructure accounted for are reparation or replacement of driveways, bridges, tunnels and rockfall and avalanche galleries. The damage type casualties will also be expressed in costs and is based on a value of 5 million CHF per human life. Casualties can occur due to direct hits of cars or due to collisions with landslide deposits or cars that are directly hit by natural hazards. Therefore, variables that are included in the risk calculation are the maximum speed defined at the highway section, the average number of cars passing daily, the probability of having a traffic jam, the lethality of the people in a car being hit by a landslide or colliding with landslide deposits, etc... Permanent landslides are assumed not to cause the damage type "casualty due to direct hit of a landslide". However, the damage type "casualty due to collision with landslide deposits can occur due to permanent landslides, but only if the intensity is medium or high. All details of the NHNR methodology for hazard and risk analysis can be found in ASTRA (2008).

3.2 Risk calculation

Similar to Fell et al. (2005), all risks for the different damage types will be calculated with the following equation:

$$R_{i,j} = f_j \times p_{i,j} \times A_i \times v_{i,j}$$

Where $R_{i,j}$ = the risk of object i during scenario j; f_j = the frequency of scenario j; $p_{i,j}$ = the probability that the object i is exposed to scenario j; A_i = the monetary value of object i; $v_{i,j}$ = the vulnerability of object i to scenario j. The methodology of ASTRA (2008) provides all required parameter values for calculating the risk for all mentioned damage types and natural hazard scenarios. Presenting them here would go further than the scope of the article. To illustrate the risk calculation, we present an example below. This example is not a result from the project, because the first results are expected in April 2009.

3.3 Landslide risk analysis example

This example deals with a shallow debris flow slide that actually occurred in 2005 in Herderenwald, Ennetbürgen, Switzerland. In this example we will concentrate on the calculation of the risk of direct landslide impact on cars present on the highway. The data of this slide used in this example originate from Liniger (2006). The slide plane was found at the limit between bedrock and loose rock and soil material. The slide was caused by extreme pore water pressures and exfiltrating karst water. The source area covered about 20 m × 30 m × 1.5 m, the transit and deposit area approx. 8500 m^2. The estimated slide volume originating from the source area was about 1000 m^3 and another 600 m^3 from the transit area. In addition, 900 m^3 wood was transported. The slide velocity was estimated to be several meters per second and the intensity was high. The return period of the event was defined as 100-300 yrs. The slide distance was 190 m and the height difference between the source and deposit area was 110 m.

We assume that the experts predicted the high intensity of this debris slide was correctly. Further, we assume that the experts predicted a deposit height of > 1 m and a width of 50 m on all four drive lanes of the national road. The spatial occurrence probability (Pso) is assumed to be 50 m/100 m. The summed average daily traffic on this highway (ADT) is 12500 vehicles per day and the maximum speed (Vmax) is 120 km/h. Traffic jams occur on average 9 days per year with a mean duration of 15 minutes (= 0.25 hrs/day).

The first step of the risk calculation is calculating the occurrence frequency of the debris slide with a return period of 100 - 300 yrs. To exclude the occurrence probability of rarer events with larger return periods in the frequency calculation, this is done following:

$$f_j = 1/100 - 1/300 = 0.0067$$

The occurrence frequency of an event with a return period of 30 or 100 years more would be respectively 1/10 – 1/30 or 1/30 – 1/100.

The next step is calculating the probability that the object i is exposed to scenario j, or in other words, that a certain damage type occurs given the scenario j. Therefore, each damage type has its own probability. The first question to answer would be whether the given meteorological conditions, the road would have been closed. According to the methodology, the probability of closure p_{sp} for this road would have been 0.1. The probability of this road not being closed equals to $1 - p_{sp} = 0.9$.

The next step is calculating the probability of having a traffic jam p_{tj}, which is done following:

$$p_{tj} = p_{tj/yr} \times p_{tj/day} = 0.00026$$

Where $p_{tj/yr}$ is the probability of having a traffic jam per year (= 9/365) and $p_{tj/day}$ is the probability of having a traffic jam per day (= 0.25/24). Now should be calculated how many cars are present on the highway during a traffic jam (Nctj):

$$Nc_{tj} = 140 \times nDL \times Sw / 1000 = 28$$

where 140 = the maximum number of cars per km drive lane in a traffic jam; nDL = number of drive lanes; Sw = the width of the debris slide on the highway. The number of cars on the highway in a normal situation would be:

$$Nc = (AHT \times \text{slide width}) / (Vmax) = 0.22$$

Where AHT = average hourly traffic = ADT/24 hrs = 12500/24 = 520.83. The slide width is given in km. Using the defined occupation rate (O_r) of 1.74 persons per car, the number of exposed persons in the traffic jam Np_{tj} would be 48.7. The amount of damage (nr. of casualties) in case of a traffic jam Dam_{tj} can now be calculated with:

$$Dam_{tj} = Pso \times Np_{tj} \times \lambda = 7.3$$

Where Pso is the spatial occurrence probability = 0.5. The amount of damage in a normal case:

$$Dam = Pso \times Nc \times O_r \times \lambda = 0.057$$

where λ = lethality in case of a shallow debris slide with a high intensity = 0.3.

The damage probability in case of a traffic jam Df_{tj} can be calculated as:

$$Df_{tj} = f_j \times (1 - p_{sp}) \times p_{tj} = 1.6E\text{-}6$$

The damage probability in a normal case =

$$Df = f_j \times (1 - p_{sp}) \times (1 - p_{tj}) = 0.006$$

The risk R can finally be calculated with:

$$R = (Df \times Dam) + (Df_{tj} \times Dam_{tj}) = 3.58E\text{-}4$$

To express this risk in monetary terms, it should be multiplied with the value of 5 million CHF per human life, which then equals 1788 CHF/yr or 18 CHF/m.yr on this section of the highway.

3.4 Risk map and planning protective measures

The example illustrated in this paper only dealt with a direct impact of a landslide with a return period of 100-300 yrs on vehicles present on the highway. Other damage types and probability-intensity scenarios were not taken into account. In the Swiss-wide project, the total risk resulting from all natural hazards, with all possible scenarios and all defined damage types will be calculated and presented as individual death probabilities or CHF/m.yr. The goal of such a risk map is to have an objective basis for planning protective measures. At present, the FEDRO foresees that those highway sections with a individual death probability higher than 1E-5, or more damage than 100 CHF/yr.m or 10'000 CHF per highway section exposed to a single natural hazard, will have highest priority in the protective measure planning and execution.

4 CONCLUSIONS

It is clear that the project presented here is an ambitious project, both in terms of its extent and the defined objectives. The methodology that has been developed is exhaustive, allowing a very detailed risk calculation and evaluation. In itself, it is a good basis for a standardized risk map of the entire Swiss national road network. The key problem to solve is of course how the assessment of the different types of natural hazards, including the definition of their probability and intensity scenarios can be standardized. The methodology is based, as much as possible, on existing guidelines on natural hazard assessment, which are widely applied by Swiss geotechnical bureaus. Nevertheless, the different levels of know-how and working methods of the expert bureaus, which will be assessing the different hazards throughout Switzerland, will largely determine the final outcome, especially in the case of landslide hazard assessment. The challenge faced by both federal offices is to assure, as much as possible, a standard working method, by accompanying those bureaus closely. In that respect, we are open for all suggestions that help fulfilling this task.

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