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Abstract

Geohazards such as earthquakes or landslides represent a major risk to structures. In this contribution risk acceptance criteria for structures subjected to geohazards are reviewed. Especially the implementation of human safety and cost benefit considerations are discussed. Current trends in the definition of target safety criteria for structures subjected to earthquakes and landslides are presented and conclusions regarding codified criteria are drawn.

Introduction

The concept of risk acceptance criteria is widely used in many industrial sectors. Comparative risk thresholds have been established which allow a responsible organisation (or regulator) to identify activities which impose an unacceptable level of risk on the participating individuals or society as a whole.

Risk acceptance can be defined by two different methods: implicitly or explicitly. Implicit criteria often involve safety equivalence with other industrial sectors (e.g. stating that a certain activity must impose risk levels at most equivalent to those imposed by another similar activity). In the past, this approach was very common because some industrial sectors (for example nuclear and offshore) developed quantitative risk criteria well before others, and thus also constituted a basis for comparison. While this methodology has been surpassed by more refined techniques, it is still used occasionally today. Explicit criteria are now applied in many industrial sectors, as they tend to provide either a quantitative decision tool to the regulator or a comparable requirement for the industry when dealing with the certification / approval of a particular structure or system.

Geohazards such as earthquakes or landslides represent a major risk to civil structures. In this contribution risk acceptance criteria for structures subjected to geohazards are reviewed. Trends in the definition of practical target safety criteria for structures subjected to earthquakes and landslides are thereby discussed.

Factors Influencing Risk Acceptability

The nature of risk determines its acceptability which is associated with several properties of it and related factors such as (Osei et al., 1997): Voluntary vs. involuntary, controllability vs. uncontrollability, familiarity vs. unfamiliarity, short/long-term consequences, presence of existing alternatives, type and nature of consequences, derived benefits, presentation in the media, information availability, personal involvement, memory of consequences, degree of trust in regulatory bodies. In the landslide case for example, natural and engineered slopes can be considered as voluntary and involuntary, respectively.

When people are familiar with risk involved in an activity they are more willing to accept it. Societies experiencing frequent landslides and/or earthquakes may have different level of landslide risk acceptance than those experiencing rare landslide and/or earthquake situations. Risk acceptability is also influenced by the failure/accident consequences. For example people leaving on a slope which has very small movement rate may accept the landslide risk unless the movement is accelerated by a triggering event. Existence of alternatives has also impact on the level risk acceptability. If there are no alternatives, many risks can be tolerated by the people.

Type and nature of consequences are another important property of risk, since risks due to events causing more damage and fatality are more difficult to accept (e.g., landslides threatening an rural area vs. earthquake in an urban area). Derived benefits of society and the individual play significant role in risk acceptance. In addition, presentation of consequences of a geohazard in media has some influence on risk acceptability. The risk acceptance depends on also level of available information, personnel involvement, memory of consequences and degree of trust in regulatory bodies. Informed societies can have better preparedness for natural hazards, while societies having frequent natural disasters have fresh memories about the consequences.

Human Safety

Acceptable risk levels cannot be defined in an absolute sense. Each individual has their own perception of acceptable risk which, when expressed in decision theory terms, represents their own "preferences". Two types of human risks are in general used, the individual and the societal risk.

The annual probability of being harmed describes the risk to an individual due to a hazardous situation. This probability is called the individual risk. With respect to fatality risks, the individual risk is the annual probability of being killed. The individual risk can also be defined as the frequency at which an individual may be expected to sustain a given level of harm from the realisation of specified hazards such as geohazards. The individual risk criterion is occasionally used for the definition of acceptable risk values in landslide hazards.

For major hazards the societal risk is important. To society as a whole or to a company or institution responsible for a specific activity, the total damage due to a hazard is of prime interest. To comprehend this point of view the notion of collective risk R (fatalities/year) is introduced.

$$R = \sum_{i=1}^{n} p_i \cdot C_i$$

(1)

In Eq.1 n is the number of all independent and mutually exclusive accident scenarios i, p_i is the probability of occurrence (per year) of scenario i, and C_i are the consequences of scenario i. Collective risk is also referred as total risk in landslide risk assessment (e.g. Fell, 1994). With respect to fatality risks the collective risk R corresponds to the annual expected number of fatalities. It depends on the probability as well as the size of the consequences of harmful events. In most practical studies the societal risk of an installation is given in the form of a numerical F-N-curve. An F-N-curve (N represents the number of fatalities, F the frequency of accidents with more than N fatalities) shows the relationship between the annual frequency F of accidents with N or more fatalities. The acceptable region, the unacceptable region, and the ALARP (as low as reasonably possible) region are thereby identified as shown in Figure 1.

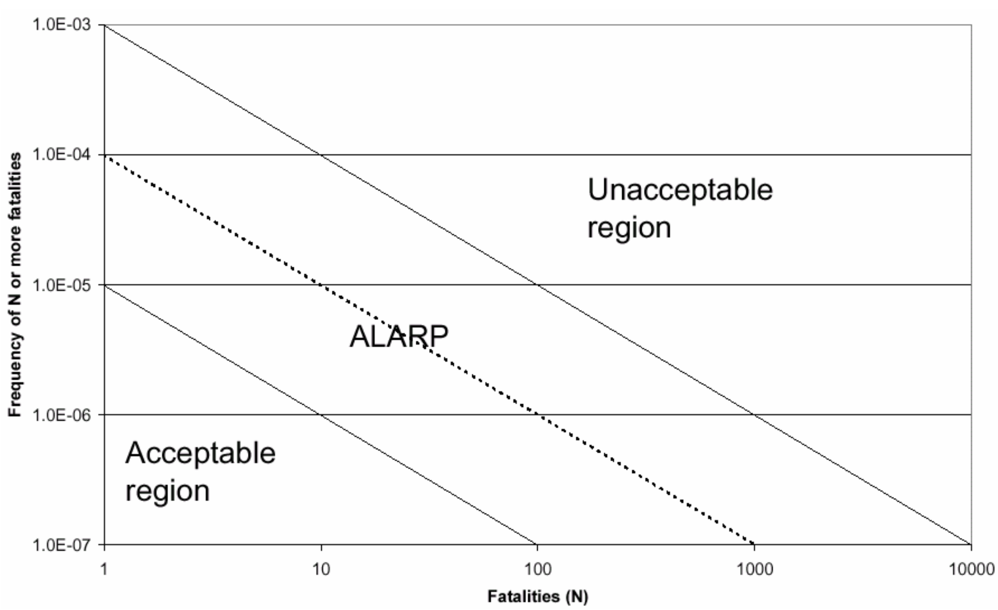

Figure 1: F N-curve and illustration of ALARP range

F-N curves form the basis of developing societal acceptability and tolerability levels. However, it is to be noted that as F-N curves are frequently derived based on historical data in the form of number of geohazards and related fatalities and consequently they represent the current situation.

The recommendations of Figure 1 can be represented in a so-called risk-matrix. For that purpose qualitative hazard probability levels suitable for use in assessment of geohazards are used together with hazard severity levels of accidental consequences. The hazard probability levels and the hazard severity levels can be combined to generate a risk classification matrix. The authority is usually responsible for defining the tolerability of the risk combinations contained within the risk classification matrix.

Direct Cost Benefit Approach

A number of areas of concern have been pointed out regarding the validity of the ALARP criteria including public participation, political reality, morality and economics. The problem of identifying an acceptable level of risk can also be formulated as an economic decision problem. The optimal level of safety corresponds to the point of minimal cost. The optimisation problem can be solved using the Life Quality Index (LQI) approach (Rackwitz, 2002). The strategy is based on a social indicator that describes the quality of life as a function of the gross domestic product, life expectation, and the life working time. The LQI (Nathwani et al, 1997) is a compound societal indicator, which is defined as a monotonously increasing function of two societal indicators: the gross domestic product per person per year g, and the life expectancy at birth e as follows:

$$L = g^{w} e^{1-w} \qquad (2)$$

The exponent w is the proportion of life spent in economic activity. In developed countries it is assumed to $w \approx 1/8$. Using this Life Quality Index Criterion, the optimum acceptable Implied Cost of Averting a Fatality (ICAF) can then be deduced:

$$ICAF = \frac{ge}{4}\frac{1-w}{w} \qquad (3)$$

It should be noted that the value expressed by Eq. 3. is not the value of one life. ICAF is not the amount of a possible monetary compensation for the relatives of the victims of the occurrence but just the monetary value, which society should be willing to invest for saving one life according to its ethical principles. Other and more refined expressions on the value of statistical life can be found in the literature.

Target reliability values and associated safety factors for design can be optimised on such a basis, depending upon type of structure and associated consequences in case of an accidental event (failure). Also safety measures can be selected by introducing the aforementioned methodological aspects. By applying the safety vs. cost-benefit approach risk acceptability criteria are indirectly applied by evaluating each investment into safety. For each possible safety measure k the following parameters are therefore considered:

C_{Ik} : Investment costs
C_{Ak} : Annual maintenace/operation costs
T: Desired lifetime of measure
dR_k: Risk reduction due to measure k divided into :

> dR_{Hk} reduction related to human risk
> dR_{Ck} reduction related to economic risk

In addition if we consider a discount rate $\delta(t)$ the evaluation of each individual safety measure can be made on the basis of the aforementioned assumptions related to risk acceptability, cost functions and risk reduction by the following inequality:

$$(C_{Ik} \text{ x } \delta(T))/T + C_{Ak} < ICAF \text{ x } dR_{Hk} + dR_{Ck} \quad (4)$$

If the inequality is satisfied then the safety measure is beneficial. However it is mentioned that the parameters entering (4) are associated to significant variabilities and therefore sensitivity analyses are necessary in order to analyse the results.

Towards Codified Criteria

In terms of reliability based approach the structural risk acceptance criteria correspond to a required minimum reliability herein defined as target reliability. The requirements to the safety of the structure are consequently expressed in terms of the accepted minimum reliability index or the accepted maximum failure probability.

The target safety depends mainly on the consequences in case of failure as well as on the relative costs of safety measures. A safety class differentiation principle is usually applied and target reliability values for ultimate limit states are proposed in Table 1. The values in Table 1 are valid for structural components and for one year reference period and are obtained based on calibration and cost benefit criteria as also discussed above (JCSS, 1999 and 2005) and reflect the background values used in the calibration of the Eurocodes.

Table 1: Target reliability indices β (and associated target failure probabilities p_F)

Relative cost of safety measure	Minor consequences of failure	Moderate consequences of failure	Large consequences of failure
Large (A)	β=3.1 ($p_F \approx 10^{-3}$)	β=3.3 ($p_F \approx 5x10^{-4}$)	β=3.7 ($p_F \approx 10^{-4}$)
Normal (B)	β=3.7 ($p_F \approx 10^{-4}$)	β=4.2 ($p_F \approx 10^{-5}$)	β=4.4 ($p_F \approx 5x10^{-6}$)
Small (C)	β=4.2 ($p_F \approx 10^{-5}$)	β=4.4 ($p_F \approx 5x10^{-5}$)	β=4.7 ($p_F \approx 10^{-6}$)

The values of Table 1 have been proposed for the design of new structures. For existing structures the costs of achieving a higher reliability level are usually high compared to structures under design. For that reason the target level of existing structures should be lower. A reduction of the reliability index β by 0.5 is recommended.

A performance based design is applied in case of earthquakes (Hamburger et al, 2003). The target reliability values can be thereby implemented for design purposes. The frequently used design return period for verification purposes can be easily obtained based on first-order reliability considerations from:

$$T = -1 / \ln (1 - \Phi(-\alpha\beta)) \quad (5)$$

with:

T: return period for design purposes
Φ( ): standard normal integral
α : sensitivity factor of earthquake hazard
β: target reliability index

However, for landslides, the establishment of target reliability indexes is a more complicated task. The main difficulty comes from the nature of the landslide phenomenon, which is discrete or local and does not have any measure of hazard magnitude like the earthquake. Usually for rapid slides such as rock falls, debris flows, etc. the structures on the landslide and in the run out area of the landslide are subjected to highest risk. Establishment of target reliability indexes for the structures in such landslide situations, requires first the prediction of landslide run out area boundary and potential energy impact produced by the slide to the structures within the boundary of the run out area. For creeping type of landslides, the position of the structure with respect to slide and the rate of movement should be taken into account. Furthermore, in the landslide case, the construction of slopes or safety assessment of existing natural and manmade slopes are of primary concern.

Hence target reliability indexes for the slopes should be assessed for safety evaluations. Christian et al (1994) propose a probability of slope failure in dam design as 0.001 which corresponds to a reliability index of 3.08. Genske and Walz (1991) suggest acceptable probability of failure values of 0.01 – 0.001 for rock slope, which correspond to target reliability index values of 2.33 – 3.08. After a calibration analysis of safe and instable slope situations, Düzgün et al. (2003) indicates acceptable reliability index value of 1.88 for a rock slope in a mine. As it can be inferred from the limited literature on acceptable probability of failure values for slopes, the reliability index around 2 can be used for safety assessments of natural slopes, while reliability index around 3 seems to be suitable for engineered slopes. However, there is a need for comprehensive calibration work on assigning target reliability index for natural and engineered slopes.

Criteria and guidelines for landslide risk are given by AGS (2000). Fell and Hartford (1997) proposes tolerable risk levels for natural slopes, existing and new engineered slopes as 10^{-3}, 10^{-4} – 10^{-6} and 10^{-5} to 10^{-6}, respectively. Later, these levels are also suggested by AGS (2000). Lee and Jones (2004) refer to studies for providing Hong Kong's interim risk guidelines for natural terrain landslide hazard. These studies used the term called "maximum allowable individual risk"' which is proposed 10^{-5} and 10^{-4} for new and existing slopes' respectively.

Concluding remarks

Geohazards represent a major risk to new and existing structures. Risk acceptance criteria have been discussed in this contribution. The following conclusions can be drawn:

a) The nature of geohazard affect the method of risk acceptance. For geohazards like earthquakes, in which the magnitude of hazard can be determined, risk acceptance criteria are more mature than geohazards like landslides, in which it is extremely difficult to express the hazard magnitude.
b) Risk acceptance criteria shall be based on optimisation (costs versus safety improvement); a safety class differentiation can be thereby considered.
c) In order to satisfy modern risk acceptance criteria for earthquakes three components of earthquake performance objectives are needed: ground motion level probabilistically defined, structural performance level, target reliability of achieving a performance level.
d) Assessing target reliability levels in case of landslide requires, prediction of landslide run out area and position of structure with respect to runout area. Moreover, target reliability levels should be established for slopes of various kinds based on comprehensive calibration studies.

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