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OPTIMIZATION OF SAFETY MEASURES AGAINST EARTHQUAKES BASED ON RISK ACCEPTANCE CRITERIA

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SUMMARY

Recent developments in the field of risk acceptance criteria for structures are implemented in this contribution to derive cost-optimal safety measures against earthquakes in seismic regions. The methodology consists of four steps: a) Probabilistic representation of earthquake intensity: the random peak ground acceleration for a specific region or country is probabilistically evaluated as a function of its influencing parameters, i.e. source geometry, magnitude model (including uncertainty of the upper bound magnitude), occurrence rate, error term. b) Probabilistic assessment of the correlation between earthquake intensity and structural damage (vulnerability): results from recent earthquakes are included to present the damage probability matrix for several building classes; the associated model uncertainties are taken into account. c) Formulation of risk acceptance criteria based on the Life Quality Index LQI Approach: by using this approach an optimum acceptable cost per averted fatality (ICAF) can be derived for a specific country. d) Optimization of safety measures based on the aforementioned risk acceptance criteria: safety measures against earthquake such as preventive design (safety factors) or mitigation measures (rescue measures) can be optimized by comparing the relative measure costs to the aforementioned ICAF and by considering their risk reducing effectiveness (based on experience and risk analysis background). The applicability of the proposed procedure dealing with optimisation of safety measures against earthquake is presented herein and illustrated in an example. Conclusions for further developments are drawn.

INTRODUCTION

Owing to the development of the global international economy, the society is more concerned to balance out costs and benefits of investments, particularly in the construction sector. It is not a main problem in regions, which are not exposed to natural disasters like earthquakes. These regions are sparse of incalculable occurrences and therefore risk reduction measures would be meaningless. However, if there is a need to consider seismic impacts by determining risk reduction measures, it leads to difficulties.

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This has been manifested in the two earthquakes in California and in Iran last December. Though the magnitude of both earthquakes was the same M=6.5 the earthquake in Iran caused more than 30000 fatalities while the one in California only two. Both California and Iran live with the ever-present possibility of earthquakes. Only the former, though, is properly prepared for them. It is obvious that there is a clear need for developments with respect to safety measures against earthquake especially in countries with weak economies.

As a matter of fact the intensity and the frequency of earthquakes can be approximately established, it is difficult to predict the occurrence-time and the intensity of an earthquake. Furthermore, it is difficult to specify the repercussions of a specific earthquake on a structure. In order to make the structural effects of an earthquake and the damages out of it computable, a great number of impacts ought to be considered. Moreover, it is difficult to specify the effectiveness of the safety measures and to derive decision criteria regarding their implementation.

The purpose of this paper is to propose a simple approach of cost-benefit-analysis, which enables to derive decision criteria regarding the implementation of safety measures against earthquake based on modern risk acceptance criteria.

SEISMIC HARZARD FUNCTIONS

Seismic hazard refers to how often earthquakes of a certain magnitude occur in a particular region. The worldwide seismicity catalogues can be used as basic input data to establish estimates of recurrence rates. These estimates are refined by incorporating regional seismicity models and site-specific fault data. Finally, locally adjusted attenuation laws for the horizontal peak ground acceleration are included into the hazard assessment.

The usual expression relating earthquake magnitudes with their rates of occurrence is the "magnitude-frequency formula" due to Gutenberg & Richter [6]. Considering the domain of engineering interest, $M_L \leq M \leq M_U$ it follows that the magnitude M in a region has a truncated exponential distribution. The cumulative probability distribution is given by:

$$F(M) = \frac{1 - e^{-\beta(M - M_L)}}{1 - e^{-\beta(M_U - M_L)}} \qquad (1)$$

in which:

F(M) is the probability of not exceeding magnitude M, M_L is the smallest magnitude of engineering interest (usually $M_L = 4.0$), M_U is the largest magnitude, which can be expected in the region, β is a site-specific constant. It is further noted here that the upper bound magnitude M_U can be a random variable.

In order to obtain the ground motion at the site it is necessary to adopt a relationship between the seismicity information (magnitudes) and peak ground acceleration (PGA), in terms of the hypocentral (or epicentral) distance. Such relationships are called attenuation laws. Many of them have been reported in the literature (s. Table 1 and Figure 1 for a comparison). Unfortunately, for the most of them no information on the error is given, but $\mu(\varepsilon_A) = 1$ and the coefficient of variation $V(\varepsilon_A)$ can be presumed not to be less than 0.20. It should be noticed, that peak accelerations become essentially independent of earthquake magnitude in the near of the rupture surface, and in addition strong-motion data are extremely limited in the near field. Therefore these attenuation laws are not applicable in the central area.

A rather general formulation of an attenuation law is the following:

$$A = b_1 \cdot e^{b_2 \cdot M} \cdot (\Delta + k)^{-b_3} \cdot \varepsilon_A \qquad (2)$$

where A is the horizontal Peak Ground Acceleration in fraction of g, Δ is the focal distance in km, k is a possible empirical modification factor for distance, b_1, b_2 and b_3 are attenuation coefficients, ε_A is a lognormal error term, considering scatter of the attenuation law.

The focal distance depends on the source geometry model. If fault-lines are well defined, it may be assumed that the focus occurs anywhere along the fault-line with equal probability. In many geographical regions, fault locations and their activity are not known. In such cases the distribution of the horizontal distance R from the focus to the site can be calculated under the assumption that focus locations are uniformly distributed over regions of homogeneous seismicity (seismotectonic province).

No.	**Region**	**Literature**	**b1 [% g]**	**b2 [-]**	**b3 [-]**	**k [km]**	**V(ε_A)**
1	California	Donovan (1973)	1.100	0.510	1.320	25.000	0.71
2	California	Mc Guire (1974)	0.480	0.640	1.300	25.000	0.22
3	California & Central America	Esteva & Villaverde (1973)	5.700	0.800	2.000	40.000	0.64
4	Canada	Milne & Davenport (1969)	0.040	0.990	1.390	0.000	--
5	Canada	Davenport (1972)	0.279	0.800	1.640	0.000	--
6	Japan	Katayama & Saeki (1978)	0.020	0.700	0.800	0.000	--
7	Taiwan	Mau & Kao (1978)	0.380	0.876	1.836	20.000	--
8	South Africa	Donovan & Bornstein (1977)	0.073	0.756	1.010	25.000	--
9	Central Europe	Ahorner & Rosenhauer (1975)	1.280	0.800	2.000	13.000	--
10	Greece	Makropoulos (1978)	2.200	0.700	1.800	20.000	0.50
11	Italy	Sabetta & Pugliese (1987)	0.014	0.363	0.500	25.000	0.20

Table 1: Attenuation laws, parameters

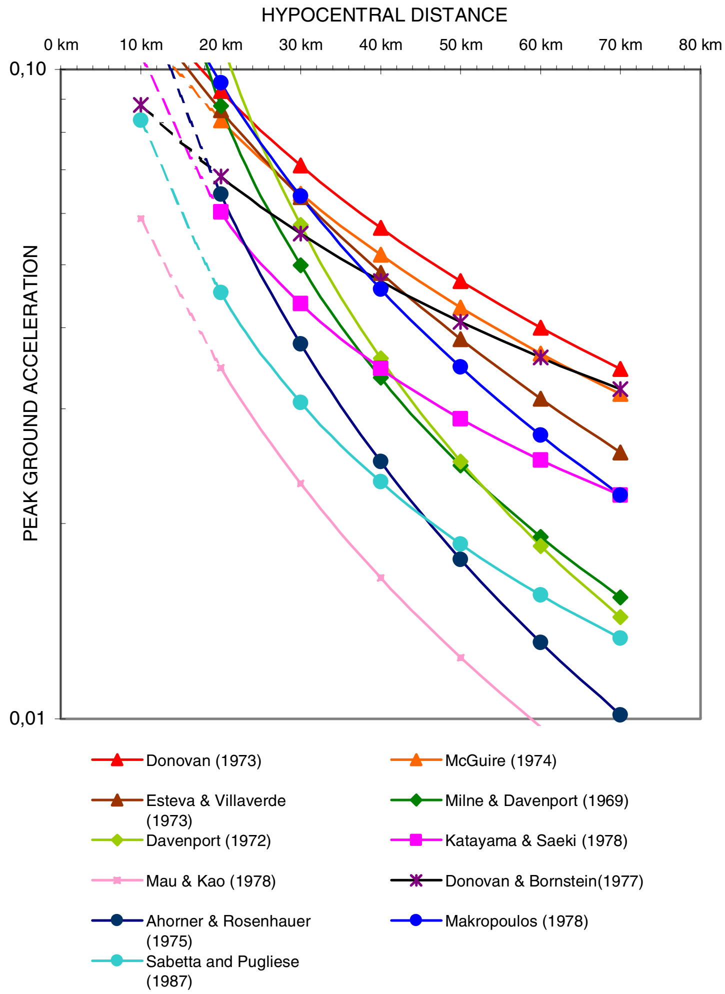

Figure 1. Comparison of Attenuation Laws for magnitude M=5.0

In good approximation, earthquakes occur according to a Poisson process with mean occurrence rate ν. The exceedence probability P [A≥a] in a reference period T per unit area can be then estimated by:

$$P[\mathrm{A} \geq a] = 1 - e^{-\nu \cdot T\, P'[\mathrm{A} \geq a]} \quad (3)$$

where:

T is the period of time and P'[A>a] is the probability of A = a given an earthquake with magnitude equal or greater than M in one source area based on the attenuation laws.

The statistical uncertainty in the estimation of ν is very important. Particularly if the observation records cover only a short period of time or the seismicity is relative small, a Bayesian model to the description of the uncertainties of ν is recommended. The following simplified expression is regressing to Benjamin [1] for the mean occurrence rate ν derived from Bayes' theorem:

$$-\nu T = \ln\left(\frac{1}{\left(1+\frac{T}{\tau}\right)^{n+1}}\right) \quad (4)$$

where n is the number of earthquakes observed in the passed time τ. In general, different potential earthquake sources must be considered simultaneously. If, for example, a site is affected by more than one ring segment then the probability P [A≥a] is obtained by:

$$P[A \geq a] = 1 - \prod_{i=1}^{m} \left(1 - P_i[A \geq a]\right) \quad (5)$$

where m is the number of the earthquake sources and P_i [A≥a] is the exceedence probability for each source.

Based on the well known aforementioned probabilistic procedure the seismic hazard at a studied site can be calculated. The procedure is included in the earthquake note of the probabilistic model code of the Joint Committee on Structural Safety [7].

DAMAGE ASSESSMENT

The damage of structural elements occurs in varying degrees. In order to forecast damages, which are expected to occur during future earthquakes, it is necessary to know how various types of structures have behaved when exposed to ground shaking of different intensities. The level of damages in a building after a given earthquake is dependent on its vulnerability and the intensity of ground motion. With increasing vulnerability, increasing damage must be expected. With small vulnerability the expected damage will have to be practically inexistent.

It is noticed that the physical damage of a structure is not only dependent on peak ground acceleration but also on the strong motion duration and the energy of the earthquake. Structural damage is also considerably influenced by frequency of ground motion and eigenfrequencies of the structure. The distribution of the wave energy in the frequency domain is considered to be an important fact because the structure under excitation is very sensitive in a few and narrow frequency ranges which represent the natural frequencies of the structures under consideration. Schuëller and Scherer [17] proposed an advanced nonstationary stochastic load model, in order to combine known deterministic solutions of linear wave equations with stochastic considerations. This would lead to an improved forecast of the pattern of the wave energy in the frequency domain for any location of interest.

Nevertheless, the optimisation methodology is based on PGA-dependent damage models. This simplification is assumed to be appropriate for investigations of spacious regions with approximately homogeneous soil properties.

A damage assessment can be specified by considering different damage parameters, such as:

- damage ratio
- injury ratio
- life loss ratio

Such an approach has been part of the HAZUS99 program (http://166.112.200.141/hazus/hazus99.htm) of the Federal Emergency Management Agency (USA). In this program various types of structures have been considered such as:

- general building stock
- essential facilities
- transportation systems (highway, railway, light rail, bus, port, ferry, airport)
- utility systems (potable water, waste water, crude and refined oil, natural gas, electric power, communication).

Besides estimation of physical damages to facilities the consideration of human losses is very important. Table 2, overtaken in extracts from Lomnitz et. al [9], shows an example of the interrelation of structural damage ratio and injuries/fatalities, appropriate for approximatively estimations of human losses. Of course, the human losses caused by disruption of transportation systems or malfunction of utility systems due to structural failure must not be neglected in the optimisation process.

Damage state and symbol	Damage ratio (%) central value	Injury ratio (%) central value	Life loss ratio (%) central value
NONE – 0	0	0	0
LIGHT – L	0.3	0	0
MODERATE – M	5	1	0
HIGH – H	30	2	0.25
TOTAL – T	100	10	1
COLLAPSE - C	100	100	20

Table 2: Relation between structural damage and human losses

RISK ACCEPTANCE CRITERIA

In recent years risk analysis techniques have gained increasing acceptance in many technical fields, including chemical and transportation industry. General consensus has been reached related to the definition of risk, but when it comes to a decision about risk acceptability controversies can be observed.

In almost all studies two points of view are chosen:
a) the point of view of the individual, who decides to undertake an activity weighing the risks against the direct and indirect personal benefits (individual risk criterion)
b) the point of view of the society, considering if an activity is acceptable in terms of the risk-benefit trade-off for the total population (societal risk criterion).

Nevertheless, the problem of the acceptable level of risk can also be formulated as an **economic decision problem**. The economic cost-benefit optimization requires suitable “life saving cost” and/or appropriate acceptance criterion if human life and limb are at risk.
The optimisation problem can be solved by using the life quality index approach. The strategy is based on a social indicator, which describes the quality of life in dependence of the gross domestic product, the life expectation and the life working time. The Life Quality Index L (Nathwani J.S. et.al. [14], Rackwitz R. [15]) 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.

$$L = g^{w} e^{1-w} \quad (6)$$

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:

$$ICAF = \frac{ge}{4}\frac{1-w}{w} \quad (7)$$

It should be noticed, that the value, expressed by eq. (7) is not the value of one life. The human life is beyond price. ICAF is also not the amount of a possible monetary compensation for the relatives of the victims of the occurrence. ICAF is just the monetary value, which society should be willing to invest for saving one life according to its ethical principles.

Figure 2 illustrates the corresponding ICAF values. They are varying considerably between countries and they reflect the socio-economical condition of the country. The ICAF value can be used in optimisation studies to define cost-optimal safety measures. It is noted, that the GDP values and the life expectancy values can be adjusted to account for other factors, such as risk aversion, discounting, etc.

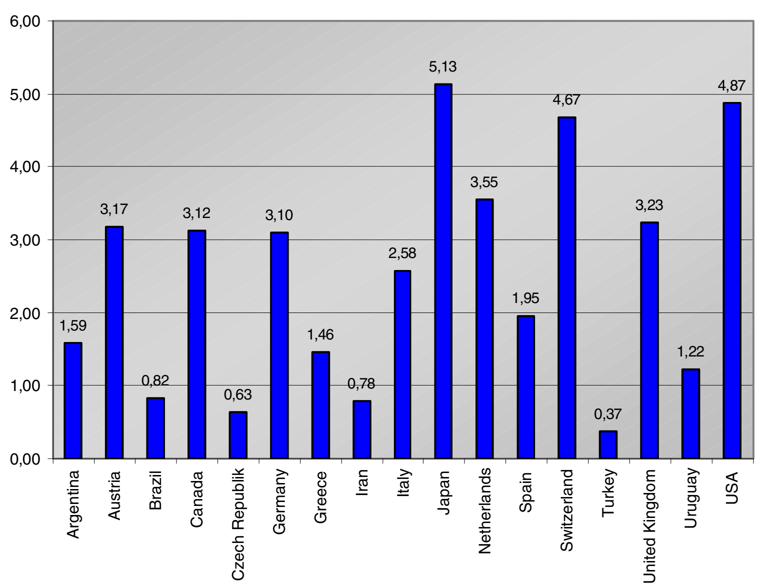

Figure 2. Comparison of ICAF for various countries based on 2001 data

Other approaches implementing the concept of the value of a statistical life might be used as done by insurance companies and national or governmental authorities. The current convention adopted for example by the Department of Transport, UK (DTLR) for the Value of Statistical Life (VOSL) is about £1,000,000 (2001 prices). This value is used in a cost-benefit evaluation of road improvement schemes in the UK.

Safety has a cost and therefore the level of safety to be guaranted for the individual member of the society is a societal decision with a strong bearing to what the society can afford. Safety related decisions should be consequently always considered in view of legal and ethical aspects. It is worthwhile to recognise that the problem concerning risk acceptance has a fundamental and philosophical bearing to the rights of human beings which are regulated by the "Universal Declaration of Human Rights."

RISK MANAGEMENT

Risk management is the process of selecting appropriate risk reduction measures and implementing them in the on-going management of the activity. The importance of managerial and organisational factors in accident causation has been shown in many disasters.

Generally two types of risk reducing measures are distinguished:

Prevention Measures
Mitigation Measures

Prevention measures

Prevention measures are measures, taken before an earthquake occures, and reduce the probability of seismic damage. Examples for prevention measures are:

- Seismic design
- earthquake and building codes
- land-use planning
- GIS mapping

In the process of seismic design, the economical point of view may not be neglected. The technical facilities should be economically optimal. This is accessible by a design-parameter-optimization in the process of cost-benefit-analysis. The purpose of a cost-benefit-analysis is the minimization of total cost C_t by applying an appropriate design parameter for seismic design or investments into other life saving measures. The total cost C_t can be calculated by:

$$C_t = C_i + p_f \cdot C_f \cdot \delta(t) \qquad (8)$$

where C_i are the initial costs of construction, including costs for safety measures ($C_{s,p}$), p_f is the probability of failure, C_f are the costs of failure and δ is a discounting function. Assumed, the costs of implementation of safety measures are proportional to the design acceleration a_d one obtains:

$$C_i = C_0 + C_{s,p} = C_0 \cdot (1 + c \cdot a_d) \qquad (9)$$

where C_0 are the initial costs without seismic design and c is a construction-type specific weighting function.

The costs of failure are dependent on the initial costs, expected damage ratio and number of fatalities, whereat expected damage ratio can be estimated by using the damage assessment methodology.

δ(t) can be obtained by:

$$\delta = e^{-\gamma t} \quad (10)$$

whereat γ is the interest rate and t is the time between decision point and time of failure. If a yearly discount rate γ' and an inflation rate η are assumed we have $\gamma = \ln(1+\gamma'-\eta)$.

The minimum of the total cost can only be derived computer aided by using numerical methods. The possible loss of human lives can be thereby evaluated by using the aforementioned ICAF values.

Mitigation measures

Mitigation measures are measures which aim to reduce the consequences (fatalities) after an earthquake. They include:

- disaster planning
- emergency management
- emergency personnel training
- rescue and response
- community education, information and mass-media
- simulated earthquake exercises
- medical preparedness

The costs of mitigation measures arise more or less continuous over the economic life of the structure. The constant annual rates C_a are to be discounted using an annuity value factor φ.

$$\varphi = \frac{(1+\gamma_r)^t - 1}{(1+\gamma_r)^t \cdot \gamma_r} \quad (11)$$

Herewith the annuity value $C_{s,k}$ of the continuous investments on the decision time t=0 is obtained by:

$$C_{s,k} = C_a \cdot \varphi = C_a \cdot \frac{(1+\gamma_r)^t - 1}{(1+\gamma_r)^t \cdot \gamma_r} \quad (12)$$

In order to take economically reasonable mitigation measures, the value $C_{s,k}$ must be less than the risk reduction ΔR (including economical loss and loss of life combined by introducing the ICAF parameter), achieved by implementation of the measure. As a matter of course ΔR must be discounted to the decision time, too.

Therewith the following requirement is obtained:

$$C_{s,k} \leq \Delta R \cdot \delta(t) \quad (13)$$

Combination of preventive and mitigation measures

Are both preventive and mitigation measures installed, the requirement states as

$$C_{s,p} + C_{s,k} \leq \Delta R \cdot \delta(t) \quad (14)$$

It should be noted, that it is difficult to estimate reliable values of the measures effectiveness (especially in terms of averted fatalities per year) and therefore this kind of cost-benefit-analysis can only provide a coarse overview of the reliability of the mitigation measure. Nevertheless, this tool may be a useful help in the decision process.

EXAMPLE

The construction costs for a bridge except safety measures are 100 mill. \$. The life time of the bridge is estimated to be 100 years. Based on the seismic hazard of the site and the damage assessment the probability of a total damage is estimated to P[total damage] = 0.0006. The total economic loss is assumed to be 1000 mill. \$ (replacement of bridge and related infrastructure, loss of use, injuries and fatalities).

In order to reduce the risk to an acceptable level the implementation of safety measures is envisaged. The costs of this measures are on one time $C_{s,p}$ = 3 mill. \$ and then annually $C_{s,k}$ = 0.1 mill \$ for the remaining economic life time of the structure. The possible loss reduction is assumed to be 40 %. The annuity value factor (interest rate 3%) is calculated to $\varphi(100) = 31.599$.

The above mentioned decision criterion reads as follows:

$$C_{s,p} + C_{s,k} \cdot \varphi(t) \leq \Delta R \cdot \varphi(t)$$

And the numerical evaluation provides:

$$3 + 0.1 \cdot \varphi(100) = 6.2\, mill.\$ < 1000 \cdot 0.0006 \cdot 40\% \cdot \varphi(100) = 7.6\, mill.\$$$

The outcome in this example shows, that the costs for the envisaged safety measures are acceptable for the investigated scenario.

CONCLUSIONS

In this paper an attempt was made to provide a probabilistic model for the optimal selection of safety measures associated to earthquake damage. This model takes into account the behaviour of structures in terms of damage ratio for earthquake occurrences with given site accelerations. The horizontal peak ground acceleration is derived by the classical approach as a function of the earthquake magnitude and the source to site distance under application of appropriate attenuation laws. The probability of exceeding a specific site acceleration can be calculated by assuming earthquake to follow a Poisson process. The rate of fatalities can be approximately assessed in dependence of the damage ratio of the building. Associated uncertainties can be taken into account. Risk acceptability criteria can be formulated by using the life-quality-index approach and the economical values of a statistical life or an implied cost to avert a fatality can be thereby obtained.

However, damage and loss can be reduced, or mitigated, in any of a number of ways. The risk management process for the mitigation of earthquake hazard involves the collaboration of many different parties with different tasks. The focal issues of the process are risk prevention and reduction. The acceptable costs for life saving measures can be assessed by using cost-benefit-analysis and the life-quality-index-criteria.

Particularly for alternative mitigation measures, the effectiveness and the monetary rentability must be further investigated in the future.

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