Seismic Risk Assessment for Typical Swiss Buildings Based on Mechanical and Empirical Approaches

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SUMMARY:
In order to check the seismic safety requirements for existing buildings in Switzerland – introduced by the Pre-Standard SIA 2018 in 2004 – a framework for seismic risk assessment has been developed. The framework is based on the probability seismic hazard assessment elaborated by the Swiss Seismological Service for 4 locations considering site effects, and fragility studies of two typical unreinforced masonry buildings carried out by the Swiss Federal Institute of Technology Lausanne. Two – a mechanical and an empirical – approaches have been followed and results are compared and discussed. Besides, uncertainties because of hazard data and due to record to record randomness as well as uncertainties concerning the fragility curves are handled in the framework.

Keywords: Risk assessment, fragility curve, damage grade, spectral acceleration and failure probability

1. INTRODUCTION

1.1. Background

Most existing buildings in Switzerland do not comply with the seismic requirements of the newest building codes of 2003. In 2004, the Pre-Standard sia 2018 was elaborated by the swiss society for engineers and architects (sia) in order to cover the problem of the seismic verification of existing buildings [Kölz et al., 2006; Vogel, 2005]. This Pre-Standard sets minimal seismic safety requirements for existing buildings and proposes cost benefit criteria for retrofitting measures based on the reduction for risk to people. In late 2012, the Pre-Standard SIA 2018 will be replaced by a new building code SIA269/8. For this new code, the safety requirements defined in SIA 2018 have to be questioned according to the current state of knowledge and new cost-benefit criteria have to be proposed in order to cover the financial risk from direct damage to the structures.

1.2. Objectives

For the purpose mentioned above and in order to support elaboration of the new building code a project was launched by the Swiss federal office for the environment (FOEN) in order to calculate the risk to existing buildings according to the newest mechanical approaches and to compare it with the intensity-based empirical approach similar to the one applied for SIA 2018. The project is composed of three main parts:

- Preparation of a consistent hazard dataset up to a return period of 10'000 years as a function of both spectral acceleration and EMS-Intensity by the Swiss Seismological Service (SED)
- Determination of the structural fragility curves of representative unreinforced masonry structures based on nonlinear dynamic numerical simulations and empirical methods
- Elaboration of a computational framework for risk calculation considering uncertainties linked with the hazard input and the fragility curves for both mechanical and empirical methods.

The elaboration of the fragility curves for the selected buildings according to the mechanical approach are addressed in a companion paper [IMAC, 2012]. The main focus of this paper is on the development of the computational framework for the risk assessment of casualty and financial losses due to direct damage and on the comparison of the calculated risk according to the mechanical and the empirical approach.

With the objectives and tasks given above, two typical Swiss buildings have been studied and exposed to seismic hazard in several locations in Switzerland. Unit casualty and unit property risks because of structural damage/collapse have been studied and compared with accepted values.

2. REQUIREMENTS OF THE RISK ESTIMATION FRAMEWORK

2.1. Probabilistic Seismic Hazard Assessment

Probabilistic seismic hazard assessment (PSHA) is done to compute the rock hazard as described in [Giardini et al., 2004; Wiemer et al., 2009]. Calculations were made for 3 sites Zurich (university campus), Basel (Munster) and Sion (old town) [Wiemer, 2011]. The hazard assessment for intensity is based on 2 intensity measures (IM):

– Spectral acceleration of the first period of vibration ($Sa(T_1)$)
– European Macroseismic Intensity (EMS-I).

The seismic hazard (spectral acceleration) has been assessed by the help of Monte-Carlo simulations [Wiemer et al., 2009], using a synthetic earthquake catalog as input. This is the same set of data used for the current SIA code 261. For this project fractiles at 10% - 90% probability of exceedance have been added. Spectral values are provided at 0.5, 1, 2, 3, 5, 10 and 12 Hz.

To compute the hazard at the surface for each site an amplification factor is provided. This factor considers the amplification of seismic waves from the (SED-) bedrock to the surface (Figure 1a). Besides, to study an extreme case the amplification factor for Rhone valley in Sion is also given, in which the same hazard data as in Sion old town has been considered. The amplification factor in the valley for the range of periods between 0.2 and 0.4 seconds is too large and results in a nonlinear response (de-amplification) of the ground motion. Hence in this case the amplification factor has been modified (Figure 1b).

Hazard assessment with EMS-I has not been provided within the 2004 Swiss hazard study. Two methods have been applied to assess the hazard based on EMS-I:

– Direct intensity prediction method (IPE) [Fäh et al., 2003; Cua et al., 2010]
– Ground motion to intensity conversion equations (GMICE) [Faenza and Michelini, 2010].

(a) (b)

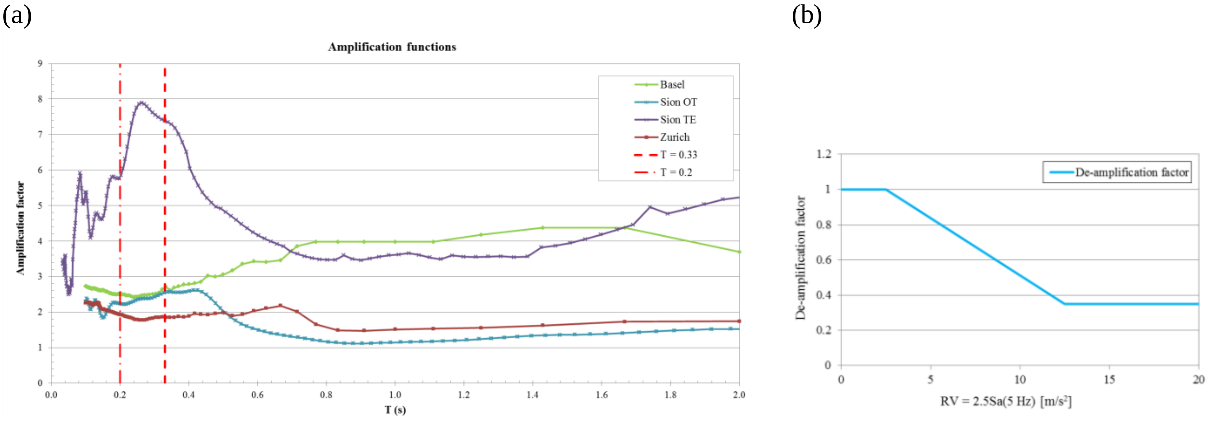

Figure 1. (a) Amplification function for Zurich, Basel, Sion and Rhone valley [Wiemer, 2011], (b) De-amplification factor for the site in Rhone Valley

(a) (b)

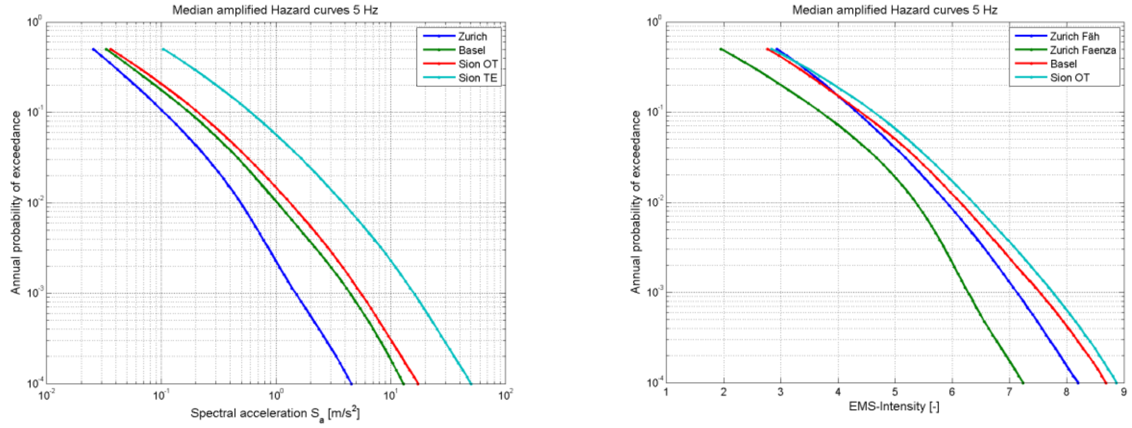

Figure 2. Median amplified hazard curves for Zurich, Basel, Sion and Sion (TE) at 5 Hz in (a) Sa, (b) EMS-I

2.2. Vulnerability

Two sets of fragility curves for 5 damage grades as a function of IM (spectral acceleration and EMS-Intensity) are derived. Fragility curves based on spectral acceleration are computed through the nonlinear dynamic analysis of the structure. Details on the selection of ground motion records, dynamic analysis of the structural system and definition of damage grades are presented in a companion paper [IMAC, 2012]. The other set of fragility curves based on EMS-Intensity are derived based on [Risk-UE, 2003].

Two buildings have been studied. Both of them are unreinforced masonry structures. Some of their structural characteristics are summarized in Table 1. Fragility curves based on EMS-I are proposed in the Risk-UE project. To compute fragility curve as a function of EMS-I a binomial distribution function has been used instead of the continuous beta distribution function suggested in Risk-UE project. Fragility curves are computed in 3 steps:

- Selection of an appropriate vulnerability class based on [EMS-98] documentation. Benchmarks studied in this project can best be categorized in vulnerability class C (masonry structures (unreinforced brick) with RC-floors). Through considering behavior modifiers (ΔV_m) the vulnerability index has been modified.
- Calculation of the mean damage ratio as a function of EMS-I and vulnerability index.
- Calculation of damage grades for the selected intensity range assuming a binomial distribution function:

$$PDF(i) = \frac{5!}{k!(5-k)!}\left(\frac{\mu_D(i)}{5}\right)^k\left(1-\frac{\mu_D(i)}{5}\right)^{5-k} \quad (1)$$

where μ_D is the mean damage grade, k is the damage grade and i is the EMS-I.

Figure 3. Selected masonry buildings, left: Chablais 30 (CHB30) and right: Yverdon 14 (YVR14) [IMAC, 2012]

Table 1. Structural characteristics of the selected buildings [IMAC, 2012]

	CHB30	YVR14
Number of stories	6	4
Year of construction	End of 19th century	1940's
Structural system	Stone masonry	Brick masonry
Floor material	RC (Retrofitted)	RC
1st mode frequency (longitudinal)	3.4 Hz	5 Hz
2st mode frequency (transverse)	3.3 Hz	5 Hz
Masonry compressive strength (normal to bed joints)	10 MPa	10.5 MPa
Masonry compressive strength (normal to head joints)	2.7 MPa	6.3 MPa
Masonry tensile strength	0.75 MPa	1.0 MPa
Wall thickness in first floor	Up to 60 cm	15 cm

2.3. Exposure

Seismic hazard exposure is an important part of seismic risk assessment. In this paper unit casualty risk and unit property risk directly caused by structural damage/collapse have been considered. Collateral or indirect damages, as for example fire and ground failure, are not covered here.

2.3.1. Direct casualty risk

Numerous factors control the casualty rate in an earthquake. The focus of the project is on the direct casualty risk related to the structural behavior. Secondary hazards are neglected. From the structural point of view there are several parameters that may affect the casualty rate of an event:

- Construction method and building type
- Workmanship
- Damage grade

The primary cause for casualties in an earthquake is building collapse. Because of this, only damage grades 4 and 5 are considered to compute the casualty risk. The probability of extensive structural damage and collapse is a function of the structural behavior, which is in turn a function of the construction method and building type [Jaiswal et al., 2011]. A casualty rate of 2% for DG4 (extensive structural damage) and 10% for DG5 (collapse) are applied:

$$P(CR \mid DG4) = 0.02$$
$$P(CR \mid DG5) = 0.10 \tag{2}$$

2.3.2. Direct property loss

To investigate the direct property loss rate of a structure, the expected monetary loss is related with the structural damage by the help of empirical relationships. The term damage ratio is defined as a function of damage grade as:

$$Damage\ Ratio = f(DG_{EMS}) = \frac{Cost\ of\ repair}{Replacement\ cost} \tag{3}$$

Only the value of the building (replacement cost) is taken into consideration and other sources of damage costs as for example damages to nonstructural elements and contents are not considered.

The ranges of damage ratios for all damage grades are given in [ATC 13, 1985; Tyagunov, 2004]. Actually, mean damage ratio is a function of not only the damage grade, but also of several other parameters as for example economic condition of the studied region or country. In a country with a stronger economy, the social acceptance to repair a badly damaged structure is much lower in comparison to a country, where there are considerably fewer resources for the replacement of damaged structures. Because of this, the SIA 269/8 working group preliminarily defined the values given in Table 2 for Switzerland, which are larger than those documented by [Tyagunov, 2004]:

Table 2. Mean damage ratio [SIA 269/8, 2011]

Classification of damage	Mean damage ratio [%]
Damage grade 0: No damage	0
Damage grade 1: Negligible to slight damage (no structural damage, slight non-structural damage)	1
Damage grade 2: Moderate damage (slight structural damage, moderate non-structural damage)	40
Damage grade 3: Substantial to heavy damage (moderate structural damage, heavy non-structural damage)	80
Damage grade 4: Very heavy damage (heavy structural damage, very heavy non-structural damage)	100
Damage grade 5: Destruction (very heavy structural damage)	100

3. RISK COMPUTATION FRAMEWORK

Risk is understood to be a function of seismic hazard, vulnerability and consequences (casualties, property loss). A deterministic seismic risk assessment concentrates on a specific seismic event, which is most of the time characterized through a ‘‘specified’’ seismic action/mechanism, i.e. known distance and magnitude. Within a probabilistic seismic risk assessment, however, a set of ‘‘possible’’ seismic actions/mechanisms is addressed. The probabilistic hazard data provided by the Swiss Seismological Service includes all possible events with return periods up to 10’000 years. Hence, in order to do the risk assessment all these relevant seismic ‘‘events’’ is taken into consideration. This is processed in several steps:

– Specification of a certain seismic event including uncertainties related to the hazard data
– Amplification of the intensity measure to consider possible site effects
– Computation of the conditional probability of a certain damage grade
– Computation of the annual probability of exceeding a certain damage grade
– Computation of the unconditional annual probability of exceeding a certain damage grade through considering all relevant events
– Computation of the unit casualty and property risks

3.1. Spectral Acceleration-Based Risk Assessment – Procedure and Example

In order to assess the risk, hazard and vulnerability data in terms of spectral acceleration have been applied. This will be demonstrated for the case where the benchmark YVR14, introduced before, is assumed to be located in Basel. Based on the frequency of the first mode of vibration of the benchmark YVR14 the hazard curve for the site Basel (Munster) at 5 Hz has been used for the computations. First of all for a selected seismic event, i.e. for a known return period, corresponding fractiles of spectral acceleration are determined. Exemplarily, this has is done for 5 events with return periods of 475, 1'000, 2'500, 5'000 and 10'000 years (Figure 4a). For each event 9 spectral acceleration values are (marked with circles) are considered. In order to investigate, how spectral acceleration’s probability distribution looks like, for all aforementioned events probability distributions are given in Figure 4b. In all cases probability distribution functions look like log-normal distribution. As expected, the standard deviations increase with increasing return periods, in a way that the coefficient of variation (C.O.V) remains almost constant.

In the next step, for the selected event, spectral accelerations are amplified to consider site effects. Then for each fractile value of the spectral acceleration the corresponding conditional probability of exceeding an arbitrary damage state must be read from the fragility curves (for each fractile value of hazard data 9 fractile values giving conditional probability of exceeding the considered damage state must be read, Figure 5). Note that in order to cover uncertainties in fragility data (record to record uncertainty) all nine fragility curves for each damage grade have been taken into consideration. The corresponding probability of exceeding an arbitrary damage grade (DG_i) for the k^{th} fractile value of the hazard as a function of the spectral acceleration is calculated by taking the arithmetic mean of nine values, which are already read. Repeating the procedure for other hazard fractiles of the event and taking the arithmetic mean value of the calculated probabilities gives the conditional probability of exceeding the desired damage grade DG_i. Note that this value is a conditional probability as it is conditioned on an arbitrary level of ground acceleration characterized by a return period or an exceedance probability (event-specific).

In the next step the annual probability of exceeding the considered damage grade for the selected event must be calculated. Therefore, the annual probability of occurrence of the event must be computed. The probability distribution function *PDF* can be computed as

$$\mathrm{CDF(Sa)} = 1 - \mathrm{H(Sa)}$$
$$\mathrm{PDF(Sa)} = \left|\frac{d\mathrm{CDF(Sa)}}{dSa}\right| = \left|\frac{dH(Sa)}{dSa}\right| \tag{4}$$

(a) (b)

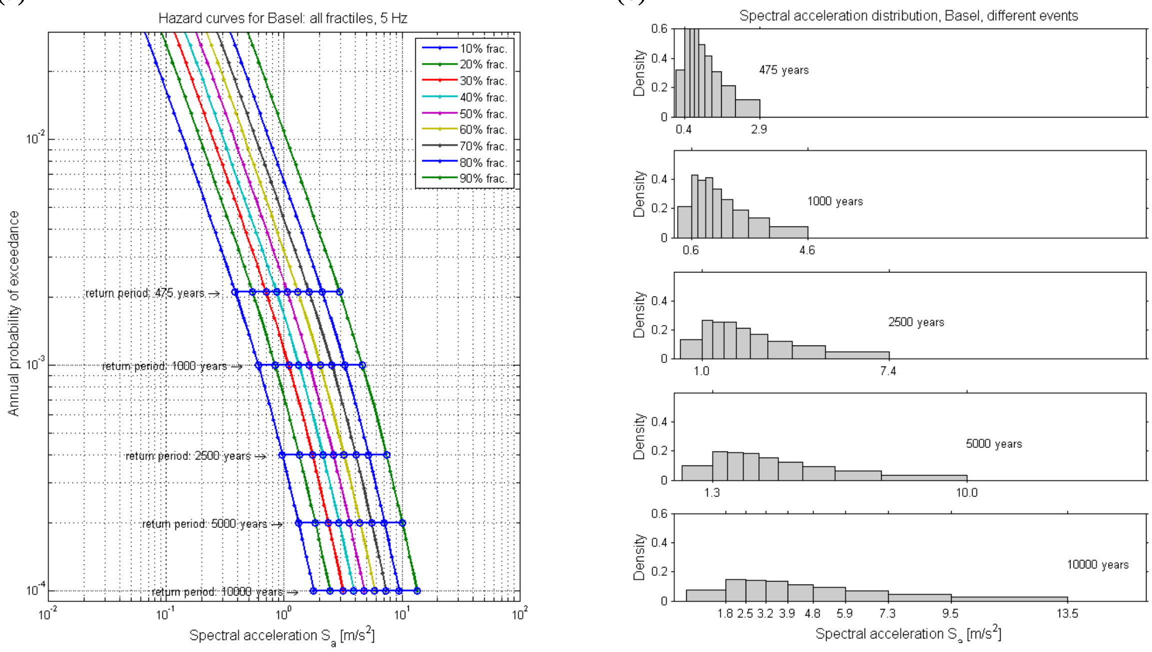

Figure 4. (a) Hazard curve for Basel (Munster) at 5 Hz, (b) Probability distributions of spectral acceleration for the selected events

(a) (b)

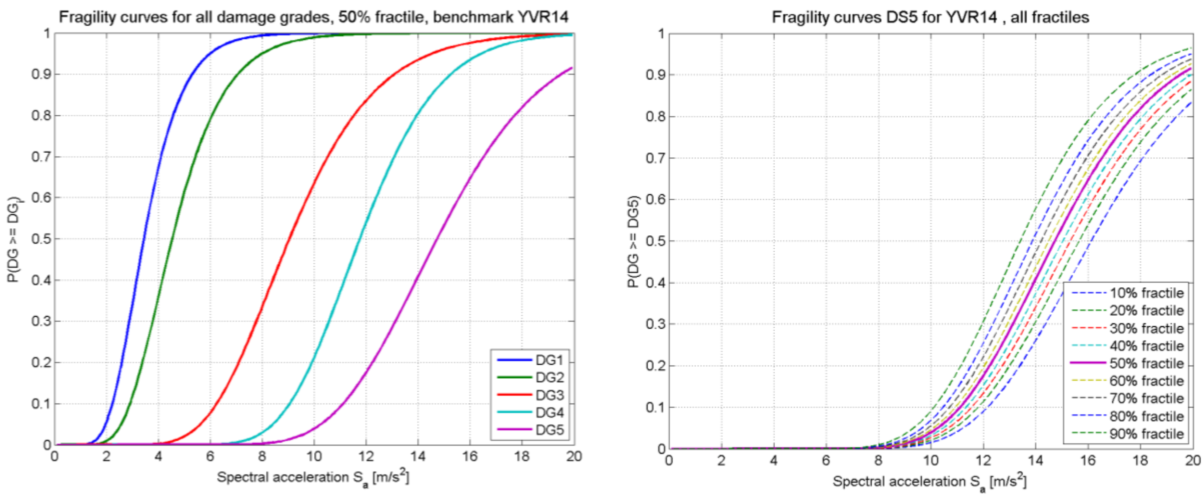

Figure 5. (a) All fragility curves for the benchmark YVR14 with 50% fractile values, (b) Fragility curves for damage grade 5 with all fractile values.

in which *CDF* is the cumulative distribution function and *H* is the hazard function (relating return periods to Sa). Multiplying this value with the conditional probability of exceeding the considered damage grade, which is calculated in the previous step, the annual probability of exceeding the considered damage grade can be computed:

$$P_{DG \geq DG_i}(Sa|T) = \left| \frac{dH(Sa)}{dSa} \right| P(DG \geq DG_i \,|Sa\,) dSa \tag{5}$$

in which $P_{DG \geq DG_i}(Sa|T)$ is the conditional annual probability of exceeding damage grade DG_i for a specific event with a return period of *T*.

Repeating the same procedure for the whole range of spectral accelerations and summing up the conditional annual probabilities of exceeding damage grade DG_i of all relevant events, the unconditional probability of exceedance of the desired damage grade can be computed (unconditional as this value is not conditioned on a specific level of spectral acceleration or a specific event). The same procedure must be repeated for other damage grades.

$$P_{DG \geq DG_i} = \int_0^\infty \left| \frac{dH(Sa)}{dSa} \right| P(DG \geq DG_i \,|Sa\,) dSa \tag{6}$$

The probability of each damage grade to occur can be calculated as:

$$P_{DG_i} = P(DG = DG_i) = P_{DG \geq DG_i} - P_{DG \geq DG_{i+1}} \qquad i = 1:4 \tag{7}$$

Hence unconditional probability of damage grades 2 to 5 are:

$$P_{DG2} = 1.4\text{x}10^{-3}, P_{DG3} = 2.7\text{x}10^{-4}, P_{DG4} = 1.3\text{x}10^{-4}, P_{DG5} = 1.7\text{x}10^{-4} \tag{8}$$

Assuming casualty rates of 10% and 2% for damage grades 5 and 4, respectively, the unit casualty risk will be $2\text{x}10^{-5}$. Based on mean damage ratios presented before, the unit property risk due to structural damage will be $1\text{x}10^{-3}$. This last value seems to be rather high in comparison to prevailing assumptions within the field of insurance and re-insurance.

3.2 EMS-Based Risk Assessment – Procedure and Example

Based on the hazard curves proposed by [Fäh et al., 2011] for the site Basel (Munster) as a function of EMS-I the risk is assessed for the benchmark YVR14, introduced before. The relevant hazard curves are given in Figure 6a. The probability distributions of the EMS-I for five return periods of 475, 1'000, 2'500, 5'000 and 10'000 years are given in Figure 6b.

The most crucial task in risk assessment based on empirical fragility data provided with the Risk-UE approach is the estimation of the vulnerability index based on the proposed values by [Lagomarsino and Giovinazzi, 2006]. The mean damage grade as a function of vulnerability index and EMS-I is contained in Figure 7a. With the aforementioned hazard and fragility data (Figure 7b), the risk has been assessed with the same method already explained in the previous section.

The unconditional probability of damage grades 2 - 5 are:

$$P_{DG2} = 1.6\text{x}10^{-3}, P_{DG3} = 4.4\text{x}10^{-4}, P_{DG4} = 9.0\text{x}10^{-5}, P_{DG5} = 1.3\text{x}10^{-5} \tag{9}$$

Assuming the same casualty rates as before, the unit casualty risk will be $3\text{x}10^{-6}$. Based on mean damage ratios given before, the unit property risk due to structural damage will be $1\text{x}10^{-3}$.

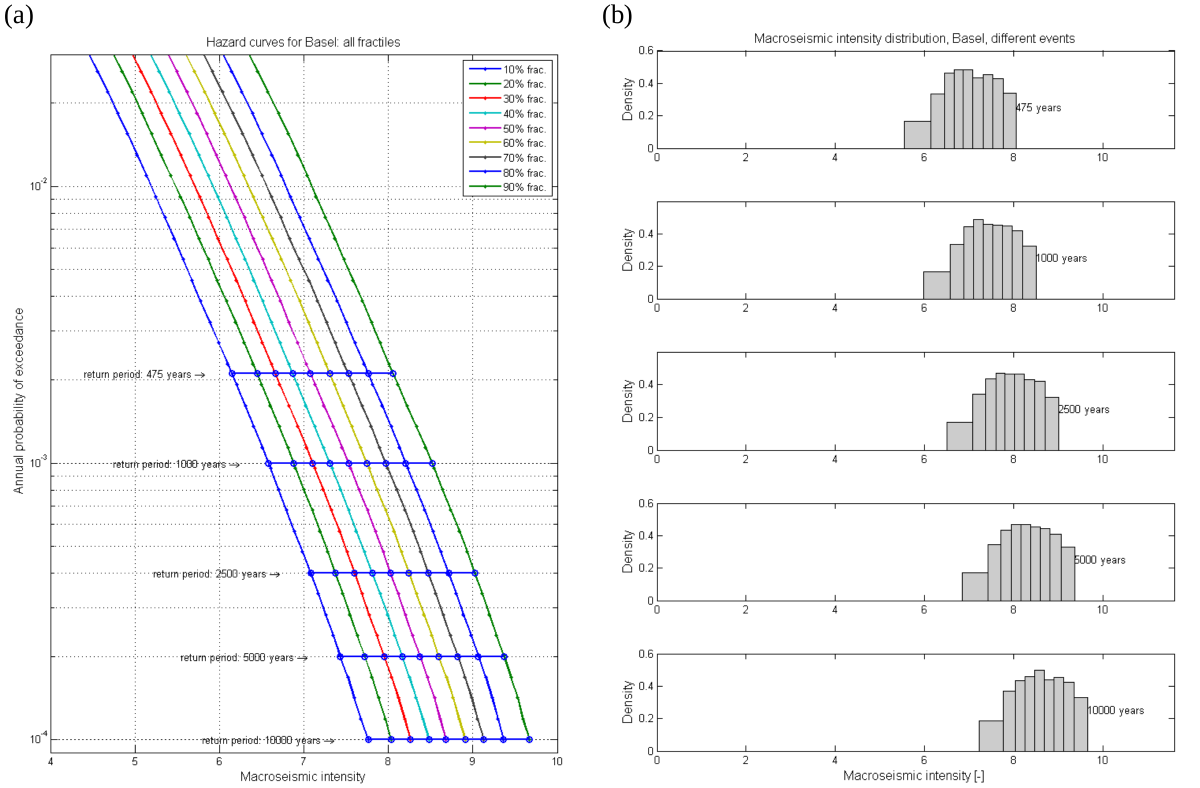

Figure 6. (a) Hazard curve for Basel (Munster) as a function of EMS-I, (b) Probability distributions of spectral acceleration for the selected events

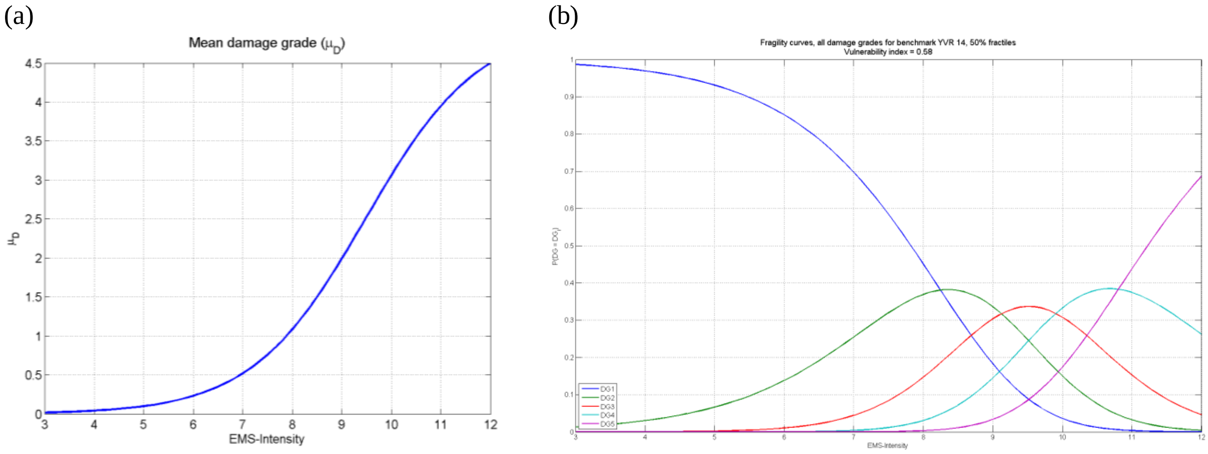

Figure 7. (a) Mean damage grade for a vulnerability index of 0.58, (b) Fragility curves as a function of EMS-I

4. RESULTS

Based on the principles introduced before, the risk for two benchmarks in 4 locations with mechanical and empirical approaches has been accessed. The results are summarized in Table 3:

Table 3. Annual probability of damage grades, unit casualty and property risks for benchmarks (a) CHB30 and (b) YVR14.

(a)

Location	Hazard	DG5	DG4	DG3	DG2	DG1	Unit casualty risk	Unit property risk [SIA 269/8, 2011]	Unit property risk [Tyagunov, 2004]
Basel	Sa	1.0E-04	4.6E-04	6.2E-05	2.7E-04	2.1E-03	2.0E-05	7.2E-04	5.2E-04
	$I_{Fäh}$	2.2E-05	1.4E-04	5.6E-04	1.7E-03	3.3E-03	5.0E-06	1.3E-03	5.3E-04
Sion OT	Sa	1.9E-04	6.9E-04	9.4E-05	3.7E-04	2.4E-03	3.2E-05	1.1E-03	8.1E-04
	$I_{Fäh}$	3.7E-05	2.0E-04	7.0E-04	1.8E-03	3.0E-03	7.7E-06	1.5E-03	6.6E-04
Sion TE	Sa	4.2E-04	3.4E-03	2.0E-04	5.0E-04	1.8E-03	1.1E-04	4.2E-03	3.3E-03
	$I_{Fäh}$	2.3E-04	6.8E-04	1.4E-03	1.9E-03	1.6E-03	3.7E-05	2.8E-03	1.5E-03
	I_{Faenza}	1.0E-04	3.8E-04	9.6E-04	1.9E-03	2.5E-03	1.8E-05	2.0E-03	9.8E-04
Zurich	Sa	1.4E-08	2.6E-05	6.2E-06	3.4E-05	5.5E-04	5.3E-07	4.5E-05	2.7E-05
	$I_{Fäh}$	8.0E-06	6.8E-05	3.8E-04	1.5E-03	3.8E-03	2.2E-06	9.8E-04	3.6E-04
	I_{Faenza}	4.3E-07	8.2E-06	1.0E-04	8.7E-04	4.7E-03	2.1E-07	4.4E-04	1.3E-04

(b)

Location	Hazard	DG5	DG4	DG3	DG2	DG1	Unit casualty risk	Unit property risk [SIA 269/8, 2011]	Unit property risk [Tyagunov, 2004]
Basel	Sa	1.7E-04	1.3E-04	2.7E-04	1.4E-03	8.5E-04	2.0E-05	1.1E-03	5.3E-04
	$I_{Fäh}$	1.3E-05	9.0E-05	4.4E-04	1.6E-03	3.7E-03	3.1E-06	1.1E-03	4.2E-04
Sion OT	Sa	3.0E-04	1.9E-04	4.1E-04	1.8E-03	8.6E-04	3.4E-05	1.6E-03	8.0E-04
	$I_{Fäh}$	2.2E-05	1.3E-04	5.6E-04	1.7E-03	3.3E-03	4.8E-06	1.3E-03	5.2E-04
Sion TE	Sa	2.3E-04	3.2E-03	2.0E-04	6.0E-04	2.0E-03	8.6E-05	3.8E-03	2.9E-03
	$I_{Fäh}$	1.5E-04	5.2E-04	1.2E-03	1.9E-03	1.9E-03	2.5E-05	2.4E-03	1.2E-03
	I_{Faenza}	6.3E-05	2.8E-04	8.1E-04	1.8E-03	2.8E-03	1.2E-05	1.7E-03	7.9E-04
Zurich	Sa	1.5E-06	4.9E-06	2.3E-05	2.4E-04	2.4E-04	2.5E-07	1.2E-04	3.8E-05
	$I_{Fäh}$	4.3E-06	4.3E-05	2.9E-04	1.4E-03	4.1E-03	1.3E-06	8.4E-04	2.9E-04
	I_{Faenza}	2.1E-07	4.8E-06	7.1E-05	7.4E-04	4.9E-03	1.2E-07	3.6E-04	1.1E-04

5. CONCLUSIONS

A computational model for earthquake risk assessment based on a mechanical and an empirical approach has been developed. Applying this model, the risk to people and the risk to property for two typical Swiss buildings at 4 different Swiss locations were calculated. Some important findings are summarized as follows:

– To consider local site effects, amplification factors given for different locations have been used. Sensitivity studies show that amplification factors are playing a predominant role with respect to the calculated risk.
– Mean damage ratio is not only a function of damage grade. In especial, the economic conditions of the studied region/country are playing an important role. If, in a well-developed country, people are rather willing to replace a building which has at most suffered damage grade three, whereas in the less developed country people cannot afford to replace the building, but must repair it, the mean damage ration in the well developed country is larger.
– Unit casualty risks computed for different locations with different methods confirm relatively well the assumptions, taken as basis of the current code (Pre-Standard SIA 2018).
– In contrast to casualty risks, the computed property risk (especially the one computed based on the suggestion for SIA 269/8) seems to be high. On one side, this value is strongly affected through assumptions made in relation between damage grade and mean damage ratio (the ratio of cost of repair to the replacement cost). On the other side, there is too few information for the calibration of such relationships, especially for countries with low to medium seismic hazard.
– Both buildings studied are made of unreinforced masonry, but each of them consists of a symmetrical and highly regular structural system with thick walls, RC-slabs and a good state of preservation. Therefore, the results show that both of them should perform fairly well in case of an earthquake.

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