Master Thesis

Towards real-time probabilistic seismic risk assessment of induced seismicity for future Swiss enhanced geothermal projects

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TOWARDS REAL-TIME PROBABILISTIC SEISMIC RISK ASSESSMENT OF INDUCED SEISMICITY FOR FUTURE SWISS ENHANCED GEOTHERMAL PROJECTS

Master Thesis

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Abstract

Deep geothermal energy is an attractive alternative green energy source with a large potential. The drawback is associated induced seismicity (IS) during reservoir creation of enhanced geothermal systems (EGS). An EGS project failed 2006 in Basel due to concerns about too high financial losses due to IS. Seismic risk mitigation is strongly needed to pave the way for future EGS projects in Switzerland and worldwide.

The core of this Master Thesis is the development of an induced seismicity risk assessment tool (ISRA) which is able to forecast probable loss time-dependent. Loss estimation in terms of financial loss, number of damaged houses and possible casualties is integrated with seismic hazard forecast models. The tool uses well-established methodologies, while its core is the damage grade estimation of buildings based on the predicted ground shaking level given in intensity units. Based on a risk study conducted after the Basel EGS in 2006, the technical functionality of the model is verified. New estimates of real financial loss caused by the Basel EGS are used to perform a model calibration. Sensitivities and limitations of the time-dependent risk assessment tool are explored.

By introducing a synthetic city data set, based on a detailed building stock of a mid-sized Swiss city, the impact of different site amplifications is demonstrated. A selection of typical subsoil conditions in the Swiss Midland and Jura has been chosen. The spatial influence of IS is shown by explicitly varying the distance between the synthetic city and the borehole.

Finally, using the developed and calibrated time-dependent ISRA calculation tools, inputs for future traffic light systems are proposed. They comprise time-dependent exceedance probabilities for a certain value of loss. Providing a traffic light system directly coupled to possible loss provides widely understood parameters to decision-makers. Accurate output quantities suitable for different interest groups are discussed. Thresholds of non-exceedance probabilities are not defined and remain subject to ongoing research and discussions.
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1. **Introduction and Background**

1.1 **Geothermal Energy – An Overview**

The increasing energy demand of today’s society combined with the request for green energy asks for new alternative energy sources. Deep geothermal energy, which is widely available in sufficient depth, is therefore an attractive alternative energy source. Low-depth geothermal energy is being widely used for heating purposes already, however deep geothermal energy is rarely used in Switzerland up to date. In order to use geothermal energy for commercial electricity production, deep layers at depths of over 3 km (with temperatures higher than 100°C) need to be exploited. Therefore deep geothermal energy systems have a great potential [Giardini, 2009].

Generally one can distinguish between two types of deep geothermal energy systems: Hydrothermal and petrothermal systems (Figure 1). In the case of hydrothermal systems, a well is drilled into a deep aquifer that contains already a sufficient amount of water for the heat exchange (the use of water from hot springs is also possible). In hydrothermal systems, almost no reservoir engineering is needed. On the other hand, in petrothermal systems wells are drilled into non-permeable hot rocks (> 100°C) without groundwater. Therefore, to ensure the heat exchange, rock porosity needs to be enhanced by pumping fluids into the rock. An enhancement is achieved by stimulating the non-porous rock layer with fluid injections at high pressures [Tenzer, 2001]. Such systems are also called enhanced geothermal systems (EGS) or originally „hot dry rock“ systems [Giardini, 2009]. This Master Thesis will only focus on petrothermal systems, which have higher potential in supplying electric energy because of the wide availability of hot dry rock. Nevertheless, applications are not only limited on petrothermal systems – it is expandable as well to hydrothermal systems or even CO₂ or wastewater storage issues.

![Figure 1: Hydrothermal systems (left) use a reservoir/aquifer containing sufficient amount of water for the heat exchange. On the contrary, in the petrothermal systems (right) the reservoir permeability needs to be enhanced by pumping liquid into the hot dry rock. [Stadt St. Gallen, 2011](modified) ](image)
1. Introduction and Background

1.2 Enhanced Geothermal Systems and Induced Seismicity

In order to create a reservoir, fluid is injected into non-porous rocks, which produces microseismicity. This phenomena, called induced seismicity (IS), is fundamental to characterise the created reservoir using an installed seismic network. An example of such a characterised reservoir can be seen in Figure 2. One of the obstacles of IS is the possibility of inducing larger magnitude events ($M_L \geq 2$) felt by humans and the potential risk they create on humans and structures. [Giardini, 2009; Kraft et al., 2009]. Still a sufficient reservoir permeability is needed to ensure fluid circulation. Therefore it is unavoidable that IS is produced. The challenge is to find the best trade-off between an optimal reservoir stimulation without creating earthquakes that damage surface structures.

Reservoir stimulation during the Basel EGS project between the 2\textsuperscript{nd} and 8\textsuperscript{th} December 2006 (referred to as Basel EGS) induced larger magnitude events, causing damage to surface structures. 11'500 m$^3$ water was injected in a 5 km deep borehole during the stimulation period. Increased seismicity is recorded with increasing injection volumes, leading to a magnitude $M_L$ 2.7 event during the injection. As a consequence, injection was stopped on the 8\textsuperscript{th} December 2006. Right after the shut-in, even a $M_L$ 3.4 event was recorded. Events with $M_L \geq 3$ are marked in Figure 2. [Häring et al., 2008]

The induced seismicity due to Basel EGS and specifically the larger magnitude events ($M_L \geq 2$) caused significant public concern. As a direct consequence, the Basel government (Kanton Basel Stadt) commissioned a study of the seismic risk resulting from continued development and subsequent operation of the geothermal system, called SERIANEX (trinational Seismic Risk Analysis Expert Group, http://www.wsu.bs.ch/geothermie). A brief overview can be found in chapter 1.3.
1.3 Basel EGS Project: SERIANEX Risk Study and Report

After the occurrence of IS in the context of the Basel EGS, which led to earthquakes of up to \( M_L \) 3.4, the goal of SERIANEX risk study \[ \text{Baisch et al., 2009} \] was to investigate whether a continued reservoir stimulation and its subsequent operation is bearable in terms of seismic risk or not. Therefore a 3D geological model of the Basel region has been developed and relevant natural fault zones with the seismic activities and recurrence times have been identified. Based on the geological model and the reservoir characteristics, numerical models have been developed in order to simulate the maximum magnitudes during a further stimulation and operation phases. A maximum possible magnitude (\( M_{\text{max}} \)) of \( M_w \) 3.7 ± 0.4 has been determined.

Using the recorded seismicity during and after the stimulation, the geological model and the assumed \( M_{\text{max}} \), a probabilistic seismic hazard and risk assessment (PSHA and PSRA) has been made for the additional hazard/risk increment of both a further stimulation and a future operational phase. Outputs are expressed in terms of financial losses, number of damaged houses and the probability of causing any casualties. Additionally to PSRA results, three deterministic scenarios, considering the occurred \( M_w \) 3.2 event (above referred to as \( M_L \) 3.4 event), as well as the for the assumed \( M_{\text{max}} \) of \( M_w \) 3.7 ± 0.4 were computed.

SERIANEX risk study considered the risk of further stimulation and a future operation as substantial. As a consequence, local authorities decided to definitely turn down the EGS project. For future EGS projects the handling of IS and its associated risk to surface structures remains a lingering question.

1.4 Efforts of the Swiss Seismological Service and Thesis Placement

To explore IS, a group called Induced Seismicity was built within the SED. The Induced Seismicity Group of the Swiss Seismological Service (SED) focuses on understanding the mechanics and physics of induced earthquakes in order to develop methods to assess the probability of occurrence of potentially damaging events \[ \text{SED, 2012} \]. In this context, tools for Induced Seismicity Hazard and Risk Assessment (hereafter called ISHA and ISRA), which is performed in near real-time, are developed. The SED distinguishes five different phases of an EGS project, each contributing its part to hazard- and risk assessment:

1. Planning Phase
2. Drilling/Logging/Testing Phase
3. Stimulation Phase
4. Operation Phase
5. Post-Operation Phase

The more advanced a project is, the more information is available. As soon as the drilling and logging phase (2) started, information about the subsoil and its seismicity become available – provided by a seismic monitoring network previously installed. Since IS occurs especially during the stimulation phase (3) and possibly also in the operational (4) and post-operational phase (5), ISHA and ISRA becomes very important.

Since IS increases with increased injection volumes (also compare chapter 1.2) it is important to control injections during the reservoir stimulation. Therefore the SED develops an advanced near real-time traffic light system which computes ISRA. Within this framework forecast models based on the measured seismicity forecast the hazard in the near future. Based on the forecasted hazard, the risk in
terms of financial loss and damaged buildings can be calculated. Figure 3 shows schematically the different steps of ISRA for future EGS systems.

![Different forecast models](image)

Figure 3: Flow chart provided by the SED how the procedure of ISRA is built up. This thesis will provide a risk calculator (red box), which is basically at the end of this chain. Also taken in account will be changes in the inventory (buildings and their values), that may change and possible thresholds in terms of acceptable risk. Graphic courtesy: [Wiemer, 2011]

1.5 Goal of this Master Thesis

This Master Thesis contributes to the ongoing efforts of the SED in developing ISRA and new advanced traffic light systems for future EGS projects in Switzerland. One of the main outcomes of this thesis is the computation of time-dependent risk in terms of financial loss and number of damaged houses based on the inventory (building stock) of cities beneath EGS projects. Necessary tools were developed to quantify the risk of IS. These tools are able to provide ISRA in different phases of an EGS project. However, in this thesis the tools were only applied to the stimulation phase. The developed tool also provides inputs for decision modules, concerning e.g. a possible stop of a stimulation. The described modules are marked in Figure 3. The main goals in detail are as follows:

1. Development of a loss estimation tool based on well-established methodologies.
2. Technical verification of the developed tool by recomputing SERIANEX results (the same input data is used).
3. Calibrating the developed tool on existing data.
4. Integrating the loss estimation tool with seismic hazard forecasting models to achieve time-dependent ISRA.
5. Exploration of the model sensitivities.
6. Provide inputs for future traffic light systems and decision-assistance modules based on the developed ISRA calculation tool.
2. Methodology

2.1 General

The methodology presented in this Master Thesis aims to assess the seismic risk produced due to IS in the context of EGS. The aim is to quantify the expected loss in terms of the number of damaged buildings, financial and human loss. Since induced earthquakes in the context of EGS are small magnitude events (observations of the Basel EGS, [Häring et al., 2008]), the focus basically lies on damages to structures (no human losses are expected). Schematically risk can be expressed as a product of hazard and vulnerability, while the expected loss is the product of hazard, vulnerability and exposure [Baisch et al., 2009; Bommer, 2002; Infrastructure and Technology Group (IST), 2004]. Although some slightly different definitions exist, standard seismic risk assessment is done as follows:

\[
\text{RISK} = \text{HAZARD} \times \text{VULNERABILITY}
\]

\[
\text{LOSS} = \text{HAZARD} \times \text{VULNERABILITY} \times \text{EXPOSURE}
\]

*Figure 4: Basic definitions of risk and loss assessment*

Loss estimation can be split into two main parts: A seismological part and a loss part (Figure 5). Input of the seismological part is the probability of occurrence of an event. Combining this information with the information of the seismic sources, Ground Motion Prediction Equations (GMPE) and local site amplifications, the probabilistic seismic hazard can be computed in terms of a seismic hazard curve. This seismic hazard curve, which is defined in terms of probability of exceedance versus ground motion amplitude is the basic input for the loss estimation part. Loss estimation takes into account the building stock at a specific site, their insurance values, number of habitants per building and the vulnerability of the buildings. An estimation of the degree of damage of the affected buildings is then computed. Combining hazard curves, vulnerability curves, building inventories, insured values and number of inhabitants/building, finally the probability of losses can be calculated [van Stiphout, 2009].

*Figure 5: Loss estimation procedure splitted in seismological and loss estimation part. (idea: van Stiphout [2009])*
2. Methodology

2.2 Seismic Hazard

2.2.1 Forecasting Seismicity

2.2.1.1 Background

A traffic light system was applied during the past EGS project in Basel based on the three components 1) public response, 2) observed local magnitude and 3) peak ground velocity (PGV) [Bommer et al., 2006; Häring et al., 2008]. Although the Basel EGS followed the traffic light system, a Ml 3.4 event occurred on December 8, 2006, 6 hours after the well shut-in [Häring et al., 2008]. The consequences as public outcries, large insurance sums paid for slightly damaged buildings and even legal actions against the operator company showed that the applied traffic light system was insufficient.

In the recent years the SED took efforts to develop probability-based traffic light systems for EGS projects. Bachmann et al. [2011] and Mena et al. [2012] developed real-time forecast models using statistical methods. These models were translated into seismic hazard in terms of probabilities of exceeding ground motion intensity levels. The major difference of ISHA to classical PSHA is that ISHA introduced in Bachmann et al. (2011) and Mena et al. (2012) is time-dependent, which means updated on the fly. Since this study aims to provide tools to calculate real-time probabilistic risk assessment, the mentioned approaches are taken as an input for the loss estimation calculations. In this study, combined forecast models, provided by Mena et al. [2012] are used.

2.2.1.2 Forecast Model: Mena et al., 2012

Mena et al. [2012] used the well-recorded Basel EGS sequences to test three different forecast model classes (Hainzl & Ogata, 2005; Reasenberg & Jones, 1989; Shapiro et al., 2010). They proposed a “combined model” which is a combination of pseudo-prospective models (model parameters are updated on the fly) of the three model classes, weighted by the Akaike Information Criterion [Kenneth et al., 2002] according to model parameters. The model has also been tested by feeding in a limited data of past seismicity to forecast the future (“learning period tests” is schematically illustrated in Figure 6). Then, seismicity rates are translated into hazard curves in terms of daily probability of exceeding European Macroseismic Scale-98 (EMS-98) intensities. An example applied on the Basel dataset can be seen in Figure 7 [Mena et al., 2012].

The seismic hazard presented in Mena et al., [2012] is taken as the hazard input for the risk calculations in this study. Therefore, a detailed description of the ISHA methodology is not included in this thesis.

![Figure 6: Basic principle of seismicity forecast.](image-url)
2. Methodology

2.2.2 Local Ground Shaking Estimation

2.2.2.1 General

Seismic hazard and risk assessment requires prediction of local ground shaking. Ground-motion prediction equations (GMPE) describe the attenuation of seismic waves from their source as a function of magnitude and distance. The level of earthquake shaking is typically indicated in terms of peak ground acceleration (PGA), peak ground velocity (PGV), spectral acceleration (SA) or intensity. In the case of EGS where IS is likely to occur, the main interest is ground shaking at the level of human perception and damage threshold. Therefore, intensity is used as the ground motion parameter in this thesis. An additional reason is the advantage in damage estimation: A certain intensity level is characterised through certain damages to buildings or humans (see also Appendix A). Consequently the use of intensity as a measure of ground shaking simplifies the estimation of damage.

Fäh et al. [2002] proposed intensity based GMPE (also called intensity prediction equation IPE) based on the earthquake catalogue of Switzerland (ECOS). It is called ECOS-02 hereafter. After calibration of the magnitudes [Bernardi et al., 2005], a revised version of the ECOS-02 IPE has been released [Álvarez-Rubio et al., 2011]. It is called ECOS-02-revised hereafter. A more recent IPE was proposed by Fäh et al. [2011] which is based on a modified data set (ECOS, version 2009). It is called ECOS-09 hereafter. These three IPEs all based on ECOS are tested for the IS sequence of Basel for the use in ISRA of Basel EGS. In addition to these three IPEs, an IPE based on global data [Allen et al., 2012] is also used (called Allen-2012 hereafter). All of these IPEs use the Modified Mercalli Intensity Scale (MMI) as intensity (see also Appendix A). The details of the selected IPEs are presented below.

Figure 7: Hazard Curves based on the combined model for 6 hours time period at day 1, 2, 3, 4, 5, 6, 9, 12 and 15. $M_{max}=5$ is considered for all curves [Mena et al., 2012].
2. Methodology

2.2.2.2 ECOS-02

ECOS-02 has been empirically derived in the framework of the ECOS-2002. Six different equations exist – distinguishing between short (< 55 km) and long distances, shallow or deep sources and seismotectonic zones (Foreland/Alpine) [Fäh et al., 2002]:

- Short-distance range (0-55 km):
  \[
  MMI = 1.27 \times M_w - 0.043 \times D + 0.096 \quad \text{(shallow)} \tag{2.1}
  \]
  \[
  MMI = 1.44 \times M_w - 0.030 \times D + 1.73 \quad \text{(deep)} \tag{2.2}
  \]

- Long-distance range (55-200 km):
  \[
  MMI = 1.27 \times M_w - 0.0115 \times D + 1.65 \quad \text{(shallow-Foreland)} \tag{2.3}
  \]
  \[
  MMI = 1.27 \times M_w - 0.0064 \times D + 1.93 \quad \text{(shallow-Alpine)} \tag{2.4}
  \]
  \[
  MMI = 1.44 \times M_w - 0.0115 \times D + 1.65 \quad \text{(deep-Foreland)} \tag{2.5}
  \]
  \[
  MMI = 1.44 \times M_w - 0.0064 \times D + 3.04 \quad \text{(deep-Alpine)} \tag{2.6}
  \]

with
\[
M_w = \text{moment magnitude}
\]
\[
D = \text{epicentral distance [km]}
\]

In this study equation (2.1) for short-distances and shallow sources is used. Standard deviation for the above mentioned equations has not been published. Therefore the mean value of the equation is used.

2.2.2.3 ECOS-02 revised

Alvarez-Rubio et al., [2011] proposed an IPE which is based on ECOS with calibrated moment magnitudes [Bernardi et al., 2005]. The set of ECOS-02-revised equations for shallow and deep events at short and long distances in both Foreland and Alpine tectonic setting are shown below.

- Short-distance range (0-55 km):
  \[
  MMI = 1.5248 \times M_w - 0.043 \times D - 0.9079 \quad \text{(shallow)} \tag{2.7}
  \]
  \[
  MMI = 1.7196 \times M_w - 0.030 \times D - 2.8941 \quad \text{(deep)} \tag{2.8}
  \]

- Long-distance range (55-200 km):
  \[
  MMI = 1.5248 \times M_w - 0.0115 \times D - 2.6539 \quad \text{(shallow-Foreland)} \tag{2.9}
  \]
  \[
  MMI = 1.5248 \times M_w - 0.0064 \times D - 2.9339 \quad \text{(shallow-Alpine)} \tag{2.10}
  \]
  \[
  MMI = 1.7196 \times M_w - 0.0115 \times D - 3.9241 \quad \text{(deep-Foreland)} \tag{2.11}
  \]
  \[
  MMI = 1.7196 \times M_w - 0.0064 \times D - 4.2041 \quad \text{(deep-Alpine)} \tag{2.12}
  \]

with
\[
M_w = \text{moment magnitude}
\]
\[
D = \text{epicentral distance [km]}
\]
As in the case of ECOS-02, the equation for shallow Foreland (equation (2.7)) is used. As well as for ECOS-02, no standard deviation for ECOS-02 revised is published. Therefore just the median is used.

### 2.2.2.4 ECOS-09

Within the compilation of ECOS-09 historical earthquakes in Switzerland were reassessed by the SED. A new attenuation law, ECOS-09, based on the compiled Swiss catalogue has been developed by Fäh et al., [2011]. Compared to ECOS-02, which contains just linear terms, the new model includes logarithmic and linear distance decay and uses hypocentral instead of epicentral distance:

\[
MMI = \frac{M_w - c_2 \ln \left( \frac{R}{30} \right) - c_3 (R - 30) - c_0}{c_1}
\]

with

- \( M_w \) = moment magnitude
- \( c_0 = \beta \)
- \( c_1 = \alpha \)
- \( c_2 = -\alpha a \)
- \( c_3 = -\alpha b \)

constants for all intensity levels and variable depth (3 – 35 km):

- \( a = -0.69182 \)
- \( b = 0.00084 \)
- \( \alpha = 0.7317 \)
- \( \beta = 1.2567 \)

Uncertainties are given in terms of standard deviations of the parameters but not in terms of MMI (since the main goal of ECOS-09 was to calibrate earthquakes based on intensity observations). As for ECOS-02 and ECOS-02-revised, just the mean values are used.

### 2.2.2.5 Allen et al., 2012 (Allen-2012)

The attenuation relationship published by Allen et al. [2012] predicts local ground shaking expressed in MMI as a function of hypocentral distance (equation (2.14) - (2.17)). Originally Allen-2012 has been calibrated for earthquakes with \( M_w \) 5.0 – 7.9 for distances between 6 and 300 km. Nevertheless, it’s applicability to IS has been tested and recommended by Douglas et al. [2012], for Basel 2006 IS sequence. Since Allen-2012 should not be considered to be reliable for hypocentral distances smaller than 6 km [Allen et al., 2012], all distances smaller than 6 km are considered to be at a distance of 6 km. This introduces an inevitable uncertainty in the near-field.
2. Methodology

- Short-distance range (Rhyp < 50 km):

\[
MMI = c_0 + c_1M_w + c_2 \ln \sqrt{R_{hypo}^2 + R_M^2}
\]  

(2.14)

- Long-distance range (Rhyp > 50 km):

\[
MMI = c_0 + c_1M_w + c_2 \ln \sqrt{R_{hypo}^2 + R_M^2} + c_4 \ln \left(\frac{R_{hypo}}{50}\right)
\]  

(2.15)

while the equation for RM is:

\[
R_M = m_1 + m_2 e^{(M_w - 5)}
\]  

(2.16)

with

\[
M_w = \text{moment magnitude} \\
Rhyp = \text{hypocentral distance [km]}
\]

\[
m_1 = -0.209 \quad c_0 = 2.085 \\
m_2 = 2.042 \quad c_1 = 1.428 \\
c_2 = -1.402 \quad c_4 = 0.078
\]

- Uncertainties (model sigma):

\[
\sigma = s_1 + \frac{s_2}{1 + \left(\frac{R_{hypo}}{s_3}\right)^2}
\]  

(2.17)

with

\[
s_1 = 0.82 \quad s_2 = 0.37 \quad s_3 = 22.9
\]

Figure 8 illustrates the model sigma (equation (2.17)) of Allen-2012 attenuation law. It is strongly distance-dependent and especially for the low distance range < 25 km values exceed 1 intensity unit. For simplicity reasons just the means of Allen-2012 attenuation law are used in this thesis.
2.2.2.6 Comparision of IPE’s with Basel 2006 IS sequence

Figure 9 compares the four IPEs considered in this study [Allen et al., 2012; Álvarez-Rubio et al., 2011; Fäh et al., 2002; 2011]. The plot shows MMI as a function of epicentral distance for the Basel earthquake of 2006, December 8 with $M_w$ 3.2 with a depth of 4.7 km [Ripperger et al., 2009].

![Figure 9: IPEs considered in this study for a $M_w$ 3.2 event with 4.7 km depth. Allen-2012 modified (dotted line) shows modifications for short distances (< 6 km) [Allen et al., 2012].](image)

Furthermore the IPEs used in this study are compared to the observed intensities for the largest induced event of $M_w$ 3.2 in Basel EGS. It is seen from Figure 10 that the observed intensities are in good agreement with the mean IPEs and fall within the sigma bands of Allen et al. [2012]. Note that ECOS IPEs do not provide any estimate of standard deviation.

![Figure 10: GMPEs compared with observed MMI of the Basel $M_w$ 3.2 event.](image)
2. Methodology

2.2.2.7 Local Site Amplifications

Earthquake ground motion on soft soils is amplified relative to hard rock sites at similar distances from the source. This is known from theory and observations [Fäh et al., 2011]. As a consequence of amplified ground motion, the earthquake impacts are higher – this includes increased damage to structures. Since local soil conditions and geology in Switzerland are very different in space, taking into account local site amplification is an important issue. Further, in the past century cities with their suburbs and industrial areas grew into former flood plains. These big alluvial plains experience very high amplification of earthquake ground motion. Buildings on such sites are especially endangered of suffering increased damage. Consequently taking into account local site amplification has an influence on loss estimation and seismic hazard, therefore it should not be neglected.

In the context of the ECOS-09 [Fäh et al., 2011], the SED published site amplification factors for intensity attenuation in Switzerland for both ECOS-02 and ECOS-09 attenuation laws. It is a classification based on geological and tectonic features of Swiss subsoil conditions. Figure 11 shows the site amplification map for Switzerland as published for ECOS-02 attenuation law.

![Figure 11: Site amplification map for Switzerland for ECOS-02 IPE [Fäh et al., 2011]](image)

The intensity amplifications were classified according to median intensity residuals between observed and calculated intensities. Figure 11 shows the median values derived for ECOS-02 attenuation law, while for big floodplains the 75th-percentile was plotted as the best amplification estimation. Since 75th-percentiles are not published for ECOS-09, they are not used in this study for both ECOS-02 and ECOS-09. It needs to be remarked, that site amplifications at locations on big alluvial plains bear big uncertainties, since most settlements that were used to compute those values are located on the edge and not in the middle of flood plains, where the amplification really would be high (personal communication with Philipp Kästli, SED). Calculations were made on the base of ECOS-02 and ECOS-09 [Fäh et al., 2002; 2011] attenuation laws and fit best for them. Since this is the most recent site amplification map covering whole Switzerland, it is also used for Allen-2012 attenuation law (see previous chapters), even if it is not explicite adapted for them.
2.3 Loss Estimation

The loss estimation tool presented here has been developed based on widely known definitions concerning building classification, vulnerability classification and damage estimation published in the EMS-98 and by Giovinazzi and Lagomarsino [2004; 2006]. Amongst others, results of the SERIANEX risk study are compared with results of the loss estimation tool described in this thesis, using the same input parameters (chapter 4).

SERIANEX risk study made different adaptations in the standard methodology presented in this thesis. One of the reasons is a very specific building stock, including three countries (Switzerland, Germany and France). Concerned are building and vulnerability classifications, as well as damage estimation and vulnerability curves. All adaptions made by SERIANEX are described in subchapters called “SERIANEX modifications”.

2.3.1 Building Stock and Classification

Settlements or city districts are assumed to be points. This means that coordinates of built-up areas were taken as settlement locations with a distinct building classification. Buildings in this study are classified based on typologies used in the European Macroseismic Scale 1998 (EMS-98) [Grünthal, 1998]. The EMS-98 divides building structures into masonry (M), reinforced concrete (RC), steel (S) and wood (W) – while those are further subdivided into building classes (BC) as e.g. M1, M2, etc. A BC is described such that the buildings belonging to the same BC have the same damage when subjected to the same ground motion. An overview of all BCs presented in the EMS-98 is given in Table 1:

<table>
<thead>
<tr>
<th>Building Class (BC)</th>
<th>Type of Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>MASONRY (M)</td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>Rubble stone</td>
</tr>
<tr>
<td>M2</td>
<td>Adobe (earth bricks)</td>
</tr>
<tr>
<td>M3</td>
<td>Simple stone</td>
</tr>
<tr>
<td>M4</td>
<td>Massive stone</td>
</tr>
<tr>
<td>M5</td>
<td>Unreinforced M (old bricks)</td>
</tr>
<tr>
<td>M6</td>
<td>Unreinforced M with reinforced concrete (RC) floors</td>
</tr>
<tr>
<td>M7</td>
<td>Reinforced or confined masonry</td>
</tr>
<tr>
<td>REINFORCED CONCRETE (RC)</td>
<td></td>
</tr>
<tr>
<td>RC1</td>
<td>Frame in RC without earthquake-resistant design (ERD)</td>
</tr>
<tr>
<td>RC2</td>
<td>Frame in RC with moderate level of ERD</td>
</tr>
<tr>
<td>RC3</td>
<td>Frame in RC with high level of ERD</td>
</tr>
<tr>
<td>RC4</td>
<td>Shear walls without ERD</td>
</tr>
<tr>
<td>RC5</td>
<td>Shear walls with moderate ERD</td>
</tr>
<tr>
<td>RC6</td>
<td>Shear walls with high ERD</td>
</tr>
<tr>
<td>STEEL (S)</td>
<td>S</td>
</tr>
<tr>
<td>WOOD (W)</td>
<td>W</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Building Class (BC)</th>
<th>Type of Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Steel structures</td>
</tr>
<tr>
<td></td>
<td>Timber structures</td>
</tr>
</tbody>
</table>

Table 1: overview of Building Classes as they appear in EMS-98.
2. Methodology

2.3.1.1 SERIANEX modifications

The SERIANEX risk study itself modified BCs, since the inventory of buildings in the Basel area has been identified and studied more detailed. SERIANEX distinguishes between 16 building classes. 9 classes are identical with the EMS-98 classification, while 7 were defined especially for the Basel area building stock [Baisch et al., 2009]. However, it was just possible to match 7 classes exactly with the EMS-98 classification. For detailed information please refer to Appendix B.

2.3.2 Vulnerability Index

The EMS-98 quantifies the number of buildings in a building class that suffer a certain grade of damage as a consequence of an earthquake as “few, many and most”. Although the quantifications “few, many and most” are associated with a certain percentage, this doesn’t allow more precise damage calculations. As a consequence Giovinazzi and Lagomarsino [2004; 2006] introduced the so-called Vulnerability Indexes (VI) with the help of fuzzy sets theory. Consequently the VI is a continuous parameter that quantifies the predisposition of a building (or a set of buildings) to be damaged by an earthquake (Giovinazzi and Lagomarsino [2004; 2006]). A VI is assigned to each building class. V_0 represents the VI for the most probable value. To account for uncertainties, lower and upper bounds of probable values were defined (V_\text{min} and V_\text{max}). Finally V_\text{min} and V_\text{max} represent the upper and lower possible values of VI (see Table 2). Values of VI range from around 0 to 1 (while VI = 0 stands for a non-vulnerable building, VI = 1 for a very vulnerable building). Values of VI for the EMS-98 classification are shown in Table 2:

<table>
<thead>
<tr>
<th>Building Class (BC)</th>
<th>V_{\text{min}}</th>
<th>V_\text{}</th>
<th>V_0</th>
<th>V_+</th>
<th>V_{\text{max}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>MASONRY (M)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>0.62</td>
<td>0.81</td>
<td>0.873</td>
<td>0.98</td>
<td>1.02</td>
</tr>
<tr>
<td>M2</td>
<td>0.62</td>
<td>0.687</td>
<td>0.84</td>
<td>0.98</td>
<td>1.02</td>
</tr>
<tr>
<td>M3</td>
<td>0.46</td>
<td>0.65</td>
<td>0.74</td>
<td>0.83</td>
<td>1.02</td>
</tr>
<tr>
<td>M4</td>
<td>0.3</td>
<td>0.49</td>
<td>0.616</td>
<td>0.793</td>
<td>0.86</td>
</tr>
<tr>
<td>M5</td>
<td>0.46</td>
<td>0.65</td>
<td>0.74</td>
<td>0.83</td>
<td>1.02</td>
</tr>
<tr>
<td>M6</td>
<td>0.30</td>
<td>0.49</td>
<td>0.616</td>
<td>0.79</td>
<td>0.86</td>
</tr>
<tr>
<td>M7</td>
<td>0.14</td>
<td>0.33</td>
<td>0.451</td>
<td>0.633</td>
<td>0.7</td>
</tr>
<tr>
<td>REINFORCED CONCRETE (RC)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RC1</td>
<td>0.3</td>
<td>0.49</td>
<td>0.644</td>
<td>0.8</td>
<td>1.02</td>
</tr>
<tr>
<td>RC2</td>
<td>0.14</td>
<td>0.33</td>
<td>0.484</td>
<td>0.64</td>
<td>0.86</td>
</tr>
<tr>
<td>RC3</td>
<td>-0.02</td>
<td>0.17</td>
<td>0.324</td>
<td>0.48</td>
<td>0.7</td>
</tr>
<tr>
<td>RC4</td>
<td>0.3</td>
<td>0.367</td>
<td>0.544</td>
<td>0.67</td>
<td>0.86</td>
</tr>
<tr>
<td>RC5</td>
<td>0.14</td>
<td>0.21</td>
<td>0.384</td>
<td>0.51</td>
<td>0.7</td>
</tr>
<tr>
<td>RC6</td>
<td>-0.02</td>
<td>0.047</td>
<td>0.224</td>
<td>0.35</td>
<td>0.54</td>
</tr>
<tr>
<td>STEEL (S)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>-0.02</td>
<td>0.17</td>
<td>0.324</td>
<td>0.48</td>
<td>0.7</td>
</tr>
<tr>
<td>WOОD (W)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>0.14</td>
<td>0.207</td>
<td>0.447</td>
<td>0.64</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Table 2: Values of vulnerability indeces VI including lower and upper bounds for the EMS-98 building classes (Giovinazzi and Lagomarsino [2004])
2. Methodology

2.3.2.1 SERIANEX modifications

Vulnerability indexes of newly defined classes were determined based on experts' judgment on the basis of the most probable value of the vulnerability index for similar structural types [Baisch et al., 2009]. SERIANEX indicates only the most probable $V_I (V_0)$. In order to provide lower and upper probable ($V_{\text{min}}/V_{\text{max}}$), $V_I$ were determined. In the case of vulnerability classes identical to EMS-98 classes, the same values were taken. For all vulnerability classes defined by SERIANEX, $V_I$ were defined based on similar classes in the EMS-98 classes. For detailed information please refer to Appendix B.

Vulnerability Factors

$V_I$ computed for building classes can be increased or decreased based on the building properties such as the number of floors, soft-stories, structural system, foundation etc. [Giovinazzi and Lagomarsino, 2004]. The vulnerability factors taken into account within the SERIANEX risk study are listed in Table 3. However, due to simplicity and easier handling for other applications (other locations where no detailed building stock is available), vulnerability factors have not been taken into account in this thesis. This may be one reason for deviations of the computed results with respect to the SERIANEX results.

<table>
<thead>
<tr>
<th>Vulnerability Factor</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of floors</td>
<td>Low (1-2)</td>
<td>-0.02</td>
</tr>
<tr>
<td></td>
<td>Medium (3, 4 or 5)</td>
<td>+0.02</td>
</tr>
<tr>
<td></td>
<td>High (6 and more)</td>
<td>+0.06</td>
</tr>
<tr>
<td>Soft-Story</td>
<td>Transformation, demolition</td>
<td>+0.04</td>
</tr>
<tr>
<td>Height of the building compared within the aggregate</td>
<td>Buildings of different heights</td>
<td>+0.04</td>
</tr>
<tr>
<td></td>
<td>Staggered floors</td>
<td>+0.02</td>
</tr>
<tr>
<td>Building age</td>
<td>&lt; 1919 (CH) or 1949 (F)</td>
<td>+0.02</td>
</tr>
</tbody>
</table>

*Table 3: Vulnerability factors with associated modifying values taken into account within the SERIANEX risk study [Baisch et al., 2009].*

2.3.3 Damage Estimation

To estimate the damage response of buildings the European Macroseismic Method (EMM) is used. The EMM which was introduced by Giovinazzi and Lagomarsino [2004; 2006] relates the Mean Damage Degree ($MDG$ or $\mu_D$) to ground motion, while ground motion is expressed in the Modified Mercalli Intensity (MMI) as published in the EMS-98 [Grüntal, 1998]. Giovinazzi and Lagomarsino [2004; 2006] published the MDG as a function of MMI and Vulnerability Index $V_I$:

$$\mu_D = \frac{5}{2} \times \left\{ 1 + \tanh \left( \frac{\text{MMI} + 6.25 \times V_I - 13.2}{2.3} \right) \right\}$$  \quad (2.18)

with

- $\mu_D$ = mean damage degree
- MMI = Modified Mercalli Intensity
- $V_I$ = Vulnerability Index
2. Methodology

2.3.4 Vulnerability Curves

Vulnerability curves correlate hazard in terms of MMI with damage expressed by the MDG (equation (2.18)). The shape of such a curve for a specific building class represents it’s behaviour at different MMI levels. Vulnerability curves only depend on the two parameters MMI and $V_i$. Figure 12 shows examples for selected $V_i$ – values, while a range from resistant ($V_i = 0.2$) to vulnerable values ($V_i = 0.8$) were taken. A more specific example can be seen in Figure 13, where the masonry building class M1 (see chapter 2.3.2) of the EMS-98 has been selected. In that case, also lower and upper probable ($V_+/V_-$) and possible ($V_{\text{min}}/V_{\text{max}}$) $V_i$ were plotted (see Table 2 for $V_i$ – values).

Figure 12: Vulnerability curves for $V_i = 0.2, 0.4, 0.6$ and $0.8$

Figure 13: Vulnerability curves for EMS-98 masonry building class M1, including lower and upper probable ($V_+/V_-$) and possible ($V_{\text{min}}/V_{\text{max}}$) bounds.
2. Methodology

2.3.4.1 SERIANEX modifications

Estimation of damage based on the mean damage degree and vulnerability indexes by Giovinazzi and Lagomarsino [2004; 2006] has been developed for events larger than the magnitude range considered in IS. Therefore the mean damage grade function (equation (2.18)) has been modified in the scope of the SERIANEX risk study [Baisch et al., 2009]. A reduction factor, depending on the level of MMI has been introduced. The SERIANEX report AP5000 and it’s appendix 2 state two different versions of this reduction factor (Table 4 and Figure 14). To reproduce the results, in this thesis version 1 has been selected. The impact of the chosen reduction factor to vulnerability curves can be seen in Figure 15. SERIANEX references to the EMS-98, where per definition MMI ≤ 3 is below the human perception level and does not cause any damage. Although the methodology introduced by Giovinazzi and Lagomarsino [2004; 2006] computes small damages to structures. Therefore SERIANEX risk study applies a reduction factor that does not allow damage to occur for MMI ≤ 3/3.5.

<table>
<thead>
<tr>
<th>reduction factor</th>
<th>Version 1 (no damage ≤ 3)</th>
<th>Version 2 (no damage ≤ 3.5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>MMI ≤ 3</td>
<td>MMI ≤ 3.5</td>
</tr>
<tr>
<td>square of the linear interpolation between:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- MMI = 3 and 6 (Vers. 1)</td>
<td>3 &lt; MMI ≤ 6.5</td>
<td>3.5 &lt; MMI ≤ 6.5</td>
</tr>
<tr>
<td>- MMI = 3.5 and 6.5 (Vers. 2)</td>
<td>MMI &gt; 6.5</td>
<td>MMI &gt; 6.5</td>
</tr>
</tbody>
</table>

Table 4: Mean damage grade reduction factors applied in the SERIANEX risk study. For the reproduction purpose, Version 1 has been selected.

Figure 14: Mean damage grade reduction factors as found in the SERIANEX risk study. To reproduce SERIANEX results in this study version 1 (no damage < MMI = 3) is used.
2. Methodology

Figure 15: Vulnerability Curves for different Vi, plotted for MMI 1 - 7, solid lines are without reduction factor, dotted lines are modified with reduction factor, version 1
2.3.5 Damage Grades

Damages to structures and buildings as a consequence of ground motion caused by earthquakes can be classified into different damage levels. According to the EMS-98 five different damage grades (DG_k with k = 1,2,3,4,5) exist. In addition DG0 is assigned for the absence of damage. DG1 represents only negligible or small damage while DG5 stands for complete destruction. Figure 16 summarizes all damage grades as they appear in the EMS-98.

![Diagram of damage grades](image)

**Figure 16: Possible damage grades (DG) of a building as they are classified in the EMS-98 [Gründtal, 1998]**

The MDG, which was introduced earlier, is a continuous non-integer measure of damage, but will be discretized into integer values (EMS-98 damage grades) in the course of the damage grade distribution calculation.
2. Methodology

2.3.6 Damage Grade Distribution

To determine the probability of occurrence of damage grades around the mean damage grade, a binomial distribution (binomial probability density function (PDF), equation (2.20)) is used. As a result, the probability \( p_k \) (with \( k = 0,1,2,3,4,5 \)) of each damage grade is obtained. Braga et al. [1982] successfully used the binomial distribution for statistical analysis of past earthquakes [Giovinazzi et al., 2006]. Figure 17 shows the distribution around a mean damage grade of 2.5. Calculating the damage grade distributions (DGD) for each building class for distinct intensities (coming from distinct magnitude events) leads to damage rate matrices (DRM) (schematically illustrated in Figure 18).

\[
\mu_D = \sum_{k=0}^{5} k \cdot p_k
\]

\[
p_k = \frac{5!}{k! \cdot (5-k)!} \cdot \left( \frac{\mu_D}{5} \right)^k \cdot \left( 1 - \frac{\mu_D}{5} \right)^{5-k}
\]

with

\( \mu_D = \) mean damage degree; \( 0 \leq \mu_D \leq 5 \)

\( k = 0, 1, 2, 3, 4, 5 \) (EMS-98 damage grades)

\( p_k = \) probability of occurrence of \( \text{DG}_k \)

Figure 17: Damage grade distribution for \( \mu_D = 2.5 \)

Figure 19 shows the DGD as a function of MMI. To give a better overview over all MMI considered, a stacked bar plot is used. Another way of illustrating the distribution of damage grades is shown in Figure 20: Probability of occurrence of each damage grade vs. MMI.
2. Methodology

Figure 19: Stacked bar plot of Damage Grade Distribution vs. MMI of a building with $V_i = 0.8$ using a Binomial PDF.

Figure 20: Fragility Curve of a building with $V_i = 0.8$. Probability of occurrences of each DG are plotted vs. MMI.
2. Methodology

2.3.7 Cost estimation

The monetary aspects of earthquake damages to structures can be measured through a ratio between repair costs and a reference cost of a building. This ratio is called Mean Damage Ratio (MDR) \cite{Cochrane_and_Schaad_1992}. The insurance profession takes the Insured Value Loss (IVL) of a building as a reference cost, while a private person is maybe more interested in the real value of its property.

However, Swiss Reinsurance Company (Zurich, Switzerland) proposed in 1992 different MDR for 10 different building classes \cite{Cochrane_and_Schaad_1992}. The SERIANEX risk study derives its cost function by the mean value of all MDR proposed by Cochrane & Schaad. In a second step, this curve was calibrated on the Basel financial losses. Values are shown in Table 5 \cite{Baisch_et_al_2009}.

<table>
<thead>
<tr>
<th>Cost function / MDR</th>
<th>Damage Grade (DG)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DG0</td>
</tr>
<tr>
<td>SERIANEX expert judgment cost function (calibrated on Basel Data)</td>
<td>0 %</td>
</tr>
<tr>
<td>SERIANEX average cost function derived from Cochrane and Schaad [1992]</td>
<td>0 %</td>
</tr>
</tbody>
</table>

Table 5: Mean damage ratios used in the SERIANEX risk study. SERIANEX finally used the „SERIANEX expert judgement curve“ which was calibrated with the paid losses after the Basel EGS project in 2006.

In this study, the SERIANEX expert judgement curve is used as a starting point and later calibrated (see chapter 5). As reference value, IVL is taken. In this thesis, the same building stock as in SERIANEX is used. It is assumed, that every building has the same IVL within a district. It remains to state, that the cost function is a very sensitive and imprecise parameter in a risk study \cite{Baisch_et_al_2009}. For a detailed discussion on sensitivities, please refer to chapter 8.

2.3.8 Casualties

Human casualty estimation is based on loss estimation models of QLARM (Earthquake Loss Assessment for Response and Mitigation) \cite{Trendafiloski_et_al_2011} and STEER (Short-Term Earthquake Risk Assessment) \cite{van_Stiphout_2009}. Both QLARM and STEER are based on event-tree models \cite{Stojanovski_and_Dong_1994} and use five different damage grades according to HAZUS [1999]. Compared to EMS-98 damage grades, HAZUS collects EMS-98 damage grades 4 and 5 to one damage grade, but distincts between non-collapse and collapse (Table 6).

<table>
<thead>
<tr>
<th>EMS-98 Damage grades</th>
<th>HAZUS Damage grades</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 no damage</td>
<td>0 no damage</td>
</tr>
<tr>
<td>1 slight damage</td>
<td>1 slight damage</td>
</tr>
<tr>
<td>2 moderate damage</td>
<td>2 moderate damage</td>
</tr>
<tr>
<td>3 heavy damage</td>
<td>3 extensive damage</td>
</tr>
<tr>
<td>4 very heavy damage</td>
<td>4-NC non-collapse</td>
</tr>
<tr>
<td>5 collapse</td>
<td>4-C collapse</td>
</tr>
</tbody>
</table>

Table 6: Comparision of EMS-98 and HAZUS damage grades. HAZUS collects EMS-98 damage grades 4 and 5, but distincts between collapse and non-collapse.
Since the methodology applied in this thesis uses EMS-98 damage grades (chapter 2.3.5), a conversion to HAZUS damage grades is necessary. Therefore MMI-based collapse matrices as used in QLARM and STEER (Table 7) are used to determine the percentage of collapsed and non-collapsed buildings in the collected EMS-98 damage grades 4 and 5. The DRM presented in chapter 2.3.6 is modified and further called modified DRM (mDRM). EMS-98 uses six different vulnerability classes (A-F) collecting different building classes with similar vulnerability indexes. Giovinazzi and Lagomarsino [2004; 2006] proposed membership functions for vulnerability indexes. According to these membership functions, building classes used in this study are assigned.

\[
\begin{array}{lcccccc}
 & MMII & & & & & \\
 VC & \leq V & VI & VII & VIII & IX & X & XI & XII \\
 A & 0 & 2 & 10 & 45 & 70 & 80 & 90 & 100 \\
 B & 0 & 0 & 3 & 10 & 40 & 50 & 80 & 100 \\
 C & 0 & 0 & 0 & 7 & 20 & 50 & 100 & \\
 D & 0 & 0 & 0 & 0 & 10 & 15 & 20 & 80 \\
 E & 0 & 0 & 0 & 0 & 10 & 15 & 20 & 80 \\
 F & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{array}
\]

Table 7: Collapse matrices for Switzerland (QLARM [Trendafiloski et al., 2011] and STEER [van Stiphout, 2009]).

VC = EMS-98 vulnerability class.

Once EMS-98 damage grades are converted into HAZUS damage grades, casualty rates can be calculated. Five casualty degrees are distinguished; C_1 stands for non-injured and C_5 for dead (Table 8). So called casualty matrices (CM) derived by QLARM and STEER from HAZUS [1999] contain the percentage of people in a building class that suffer a certain casualty degree, expressed as a function of the damage degree of the building (Table 9). Finally casualty rates (CR) can be computed by multiplying CM by mDRM (equation (2.21)).

\[
CR_k = mDRM_{VC,i} \ast CM_{k,VC}
\] (2.21)

with
k = casualty degree
VC = EMS-98 vulnerability class
i = HAZUS damage grade
2. Methodology

The number of people living in a house of a certain building class is assumed to be the total population of a settlement multiplied by the percentage of houses in that building class of the total settlement building stock.

<table>
<thead>
<tr>
<th>$C_1$</th>
<th>non-injured</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_2$</td>
<td>slightly injured</td>
</tr>
<tr>
<td>$C_3$</td>
<td>moderately injured</td>
</tr>
<tr>
<td>$C_4$</td>
<td>seriously injured</td>
</tr>
<tr>
<td>$C_5$</td>
<td>dead</td>
</tr>
</tbody>
</table>

*Table 8: Casualty degrees*

| CM-1 pertinent to vulnerability classes A and B |
|-----------------|----------------|----------------|----------------|----------------|
| 0               | 1               | 2               | 3               | 4-NC           | 4-C            |
| $C_1$           | 1               | 0.9995          | 0.99248         | 0.97796        | 0.8796         | 0.25           |
| $C_2$           | 0               | 0.0005          | 0.0035          | 0.02           | 0.1            | 0.4            |
| $C_3$           | 0               | 0               | 0.004           | 0.002          | 0.02           | 0.2            |
| $C_4$           | 0               | 0               | 0.00001         | 0.00002        | 0.0002         | 0.05           |
| $C_5$           | 0               | 0               | 0.00001         | 0.00002        | 0.0002         | 0.1            |

| CM-2 pertinent to vulnerability classes C |
|-----------------|----------------|----------------|----------------|----------------|
| 0               | 1               | 2               | 3               | 4-NC           | 4-C            |
| $C_1$           | 1               | 0.9995          | 0.99775         | 0.98898        | 0.9398         | 0.25           |
| $C_2$           | 0               | 0.0005          | 0.002           | 0.01           | 0.05           | 0.4            |
| $C_3$           | 0               | 0               | 0.00025         | 0.001          | 0.01           | 0.2            |
| $C_4$           | 0               | 0               | 0               | 0.00001        | 0.0001         | 0.05           |
| $C_5$           | 0               | 0               | 0               | 0.00001        | 0.0001         | 0.1            |

| CM-3 pertinent to vulnerability classes D, E and F |
|-----------------|----------------|----------------|----------------|----------------|
| 0               | 1               | 2               | 3               | 4-NC           | 4-C            |
| $C_1$           | 1               | 0.9995          | 0.9972          | 0.98898        | 0.9398         | 0.25           |
| $C_2$           | 0               | 0.0005          | 0.0025          | 0.01           | 0.05           | 0.4            |
| $C_3$           | 0               | 0               | 0.0003          | 0.001          | 0.01           | 0.2            |
| $C_4$           | 0               | 0               | 0               | 0.00001        | 0.0001         | 0.05           |
| $C_5$           | 0               | 0               | 0               | 0.00001        | 0.0001         | 0.1            |

*Table 9: Casualty Matrices (CM) derived from HAZUS as used in QLARM and STEER for EMS-98 vulnerability classes.*

### 2.3.8.1 SERIANEX modifications

The SERIANEX risk study uses a different method developed by Coburn and Spence [2002] which leads to a mortality rate if a building collapses. Since this thesis uses the HAZUS-derived method [HAZUS, 1999], which takes into consideration more casualty degrees, SERIANEX method is not taken into account.
2.4 Integration of Forecast Models with Loss Estimation

Probabilistic forecast models (chapter 2.2) and loss estimation (2.3) are first calculated separately and then integrated in a second step. This follows the methodology developed by van Stiphout [2009]. Figure 22 schematically illustrates the procedure: Steps 1 to 3 show the procedure to compute seismic hazard (forecast), step 4 stands for the deterministic loss estimation. Since both seismic hazard and loss estimation are computed as a function of magnitude, the two parts can be integrated by matching magnitudes (step 5). As previously explained, hazard curves used are time-dependent. Consequently, the produced probabilistic loss curves (PLC) are time-dependent as well.

![Figure 22: Flow chart of forecast models with loss estimations (idea: van Stiphout [2009])](image)

2.5 SERIANEX specific Most Probable Insured Value Loss

Additional to the probabilistic risk results the SERIANEX risk study introduced a measure called the Most Probable Insured Value Loss (MPIVL). For details please consult SERIANEX risk study [Baisch et al., 2009]. All possible combinations of hazard and damage grade probabilities that lead to a damage grade are taken into consideration:

\[
\text{Probability to observe } DGx = \sum_{\text{Intensity}=1}^{10} (\text{Prob. of occurrence of } MMI_i) \times (\text{prob. to observe } DGx \text{ under } MMI_i) \tag{2.22}
\]

with

- Prob. of occurrence of MMI, derived from hazard curve (chapter 2.2.1)
- Prob. to observe DGx under MMI, provided by the damage grade distribution (chapter 2.3.6)

Finally the probability to observe DGx can be multiplied with the cost function for DGx and the corresponding building classing. Summing up MPIVL for all building classes and locations leads to the total MPIVL for the whole study area.
3. Data

3.1 Basel dataset

The building stock Basel has been taken as published in the SERIANEX risk study. It comprises 79 settlements located within a 12 km radius around the borehole of the Basel EGS (Figure 23). Settlements are classified into small, mid-size and large towns and cities, while the city of Basel itself is subdivided into 19 districts. Building class distributions are associated according to the size of the settlements. Insured values (IV) are indicated in SERIANEX for the whole settlement, and then divided by the total number of buildings in each settlement. Since for the city of Basel just the total IV was given, in this study it has been divided by the total number of buildings in Basel. The IV does not include road infrastructures, lifelines, religious, museum, city halls, commercial and industrial buildings if they don’t consist of any residential component. Details can be found in the SERIANEX risk study, appendix 2 – AP5000 [Baisch et al., 2009]. Population figures were taken from the respective statistical offices of Switzerland, France and Germany [Baden-Württemberg, 2010; INSEE, 2011; Kanton Aargau, 2011; Kanton Solothurn, 2010; Statistik Baselland, 2011; Statistisches Amt Basel Stadt, 2012]. Mid point coordinates for all settlements have been located using Swiss national maps published by swisstopo [2012].

Figure 23: Illustration of all settlements present in the Basel dataset. Settlement points indicate the center of the built-up part of a town/city. All settlements within a radius of 12 km were considered.
Table 10 gives an example for some settlements, how informations about number of buildings, population, total IV and IV/building are stored. Table 11 shows, how the building class distribution and the associated number of buildings per building class are stored. For this example, the Basel city district of Grossbasel was taken.

<table>
<thead>
<tr>
<th>Country</th>
<th>Settlement</th>
<th># buildings</th>
<th>Population</th>
<th>total IV [CHF]</th>
<th>IV/building [CHF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switzerland</td>
<td>Basel, Grossbasel</td>
<td>491</td>
<td>2054</td>
<td>-</td>
<td>2'409'010</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Basel, Kleinbasel</td>
<td>282</td>
<td>2274</td>
<td>-</td>
<td>2'409'010</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Basel, Vorstaedte</td>
<td>565</td>
<td>4639</td>
<td>-</td>
<td>2'409'010</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Aesch</td>
<td>1891</td>
<td>10343</td>
<td>2'482'556'000</td>
<td>1'312'827</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Allschwil</td>
<td>3131</td>
<td>19804</td>
<td>4'642'731'000</td>
<td>1'482'827</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Arlesheim</td>
<td>1756</td>
<td>9021</td>
<td>2'672'989'000</td>
<td>1'522'203</td>
</tr>
</tbody>
</table>

Table 10: example for the building stock listing of Basel, comprising country, settlement name, number of buildings, population, total insured value and insured value per building.

<table>
<thead>
<tr>
<th>Country</th>
<th>Settlement</th>
<th>Building Class</th>
<th># buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switzerland</td>
<td>Basel, Grossbasel</td>
<td>M1</td>
<td>302.3</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Basel, Grossbasel</td>
<td>M2</td>
<td>33.4</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Basel, Grossbasel</td>
<td>M3</td>
<td>22.8</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Basel, Grossbasel</td>
<td>M4</td>
<td>0</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Basel, Grossbasel</td>
<td>M5</td>
<td>6.8</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Basel, Grossbasel</td>
<td>M6</td>
<td>0</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Basel, Grossbasel</td>
<td>M7</td>
<td>6.8</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Basel, Grossbasel</td>
<td>RC1</td>
<td>0</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Basel, Grossbasel</td>
<td>RC2</td>
<td>35.55</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Basel, Grossbasel</td>
<td>RC3</td>
<td>3.95</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Basel, Grossbasel</td>
<td>RC4</td>
<td>20.4</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Basel, Grossbasel</td>
<td>RC5</td>
<td>15.4</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Basel, Grossbasel</td>
<td>S1</td>
<td>6.3</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Basel, Grossbasel</td>
<td>S2</td>
<td>0</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Basel, Grossbasel</td>
<td>W1</td>
<td>0</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Basel, Grossbasel</td>
<td>W2</td>
<td>37.3</td>
</tr>
</tbody>
</table>

Table 11: example of the building class distribution of the Basel district Grossbasel, which totally consists of 491 buildings.

3.2 Synthetic city dataset (Yverdon building stock)

Thanks to the support of the Federal Institute of Technology Lausanne (EPFL) access was granted to a very detailed building stock of Yverdon produced by Lestuzzi P. et al. [accessed 06.08.2012]. Yverdon with its 27'500 inhabitants [BfS, 2012] is a typical mid-sized Swiss city. The Yverdon building stock, containing 2444 buildings is used as a “synthetic city” (as it is referred to hereafter) to perform geographically independent case studies. A purely assumptive value of 1.5 Mio. CHF per building has been taken. Table 12 and Table 13 give an overview of both the corner data and building class distribution of the Swiss synthetic city. Figure 24 illustrates the data set underlain by a topographic map.
3. Data

<table>
<thead>
<tr>
<th>total # buildings</th>
<th>2444</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>population</td>
<td>ca. 27'500</td>
<td>by 31.12.2010</td>
</tr>
<tr>
<td>IV per building</td>
<td>1.5 Mio CHF</td>
<td>assumption</td>
</tr>
<tr>
<td>total IV</td>
<td>3'666 Mio. CHF</td>
<td></td>
</tr>
</tbody>
</table>

Table 12: corner data of the synthetic Swiss city

<table>
<thead>
<tr>
<th>Building Class</th>
<th># buildings</th>
<th>% of total buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>31</td>
<td>1.3</td>
</tr>
<tr>
<td>M2</td>
<td>1</td>
<td>0.0</td>
</tr>
<tr>
<td>M3</td>
<td>227</td>
<td>9.3</td>
</tr>
<tr>
<td>M4</td>
<td>189</td>
<td>7.7</td>
</tr>
<tr>
<td>M5</td>
<td>496</td>
<td>20.3</td>
</tr>
<tr>
<td>M6</td>
<td>1394</td>
<td>57.0</td>
</tr>
<tr>
<td>RC1</td>
<td>8</td>
<td>0.3</td>
</tr>
<tr>
<td>RC4</td>
<td>17</td>
<td>0.7</td>
</tr>
<tr>
<td>RC5</td>
<td>26</td>
<td>1.1</td>
</tr>
<tr>
<td>RC6</td>
<td>13</td>
<td>0.5</td>
</tr>
<tr>
<td>S</td>
<td>19</td>
<td>0.8</td>
</tr>
<tr>
<td>W</td>
<td>23</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 13: Building Classification of the synthetic Swiss city

Figure 24: Overview of the Yverdon data set.
4. Result comparision with SERIANEX risk study

4.1 Motivation

The SERIANEX loss estimation methodology is very similar to the standard methodology which is used in this thesis. In this section, the results computed with the developed tool in this thesis are compared with the results of SERIANEX risk study. Therefore, the same building stock as used in SERIANEX is taken (compare chapter 3.1) and SERIANEX methodology adaptations are applied (see chapter 2).

A result comparision aims to check if the developed model is able to achieve similar results as in SERIANEX, when the same input data is used. Since SERIANEX risk study has never been peer-reviewed nor scientifically published, outputs given by SERIANEX are not confirmed. It is known from industry representatives (personal communication with Dr. Peter Meier, Geo-Energie Suisse) that insurance payouts as a consequence of the earthquakes in the context of the Basel EGS were very generous and obliging. It is estimated, that the total amount of approximately 8 Mio. CHF [Baisch et al., 2009] included also many damage claims not directly associated with the EGS project. The fact, that the SERIANEX loss estimation model calibration is based on the mentioned 8 Mio. CHF may cause wrong outputs in terms of financial losses and number of damaged houses.

Nevertheless SERIANEX uses well established and straightforward methods to estimate possible losses. Therefore a result comparision with the model used in this thesis still makes sense and can give a feeling how accurate it performs when using the same input data. Additionally possible mistakes in the SERIANEX risk study can be found and improved.

Both the deterministic and probabilistic results are compared. Comparisions are limited to deterministic scenarios and the Most Probable Insured Loss Value (MPILV) (probabilistic approach). Just IVL and number of damaged building of DG1 are compared. Since in this thesis and SERIANEX risk study different casualty estimation methods are used (see chapter 2.3.8), comparisions are avoided.
4. Result comparision with SERIANEX risk study

4.2 Deterministic Results

4.2.1 SERIANEX deterministic scenarios

Within the context of the SERIANEX risk study three deterministic scenarios for the distinct magnitude events $M_w=3.2$, $M_w=3.7$ and $M_w=4.1$ were computed. While $M_w=3.2$ scenario’s objective was to reproduce losses after the real $M_w=3.2$ earthquake in Basel on December 8, 2006, $M_w=3.7$ and $M_w=4.1$ scenarios are associated to the maximum magnitudes ($M_{\text{max}}$ hereafter) that have been assumed. Considering the real magnitude event $M_w=3.2$ in 2006, SERIANEX states, that total damage costs of 8 Mio. CHF have been refunded and 260 buildings were affected [Baisch et al., 2009]. Results of all SERIANEX deterministic scenarios are shown in Table 14. The IVL for the $M_w=3.2$ event is 10.52 Mio. CHF, which is around 2.5 Mio. CHF above the real pay-outs. Nevertheless, this result was accepted by the SERIANEX expert group.

<table>
<thead>
<tr>
<th>Event</th>
<th>IVL [Mio. CHF]</th>
<th># buildings in DG1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_w=3.2$</td>
<td>10.52</td>
<td>292</td>
</tr>
<tr>
<td>$M_w=3.7$</td>
<td>53.95</td>
<td>1420</td>
</tr>
<tr>
<td>$M_w=4.1$</td>
<td>158.83</td>
<td>3740</td>
</tr>
</tbody>
</table>

Table 14: Results of SERIANEX deterministic scenarios [Baisch et al., 2009].

4.2.2 Comparision using IPE ECOS-02

In order to compare SERIANEX deterministic scenarios with my model, the same methods and input parameters were used (see chapters 2 and 3). In this section, results were computed by using the IPE ECOS-02 (same as in SERIANEX) without site amplifications. Chapter 4.2.3 also presents the application of alternative IPEs. Plots in this and the next section show IVL in CHF as a function of magnitude $M_w$. Calculations were made for all events between $M_w=0.9$ (magnitude of completeness) and $M_w=5.0$ with an increment of 0.1 magnitude units.

Figure 25 shows the deterministic loss curve: Total IVL [CHF] for all settlements in the Basel area as a function of magnitude $M_w$. The reproduced loss curve fits very well to the SERIANEX data points. Table 15 and Table 16 compare the SERIANEX datapoints with the reproduced model – in terms of IVL and number of houses in damage grade 1 (DG1). Deviations with respect to the SERIANEX scenarios range from -1% up to -3% for the IVL values and from – 1% up to -4% concerning the number of houses in DG1. My model matches SERIANEX deterministic scenario data points. It is satisfactory that the results are so close to the results computed in SERIANEX.
4. Result comparison with SERIANEX risk study

Figure 25: Deterministic loss curve for IPE ECOS-02: Insured Value Loss (IVL) vs. Magnitude $M_w$.
Upper and lower plausible boundaries (V-/V+) and deterministic scenarios carried out by the SERIANEX risk study for the Magnitude events $M_w = 3.2$, $M_w = 3.7$ and $M_w = 4.1$ are included.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>SERIANEX IVL [Mio. CHF]</th>
<th>This Thesis IVL [Mio. CHF]</th>
<th>Deviation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_w = 3.2$</td>
<td>10.52</td>
<td>10.46</td>
<td>-1</td>
</tr>
<tr>
<td>$M_w = 3.7$</td>
<td>53.95</td>
<td>52.80</td>
<td>-2</td>
</tr>
<tr>
<td>$M_w = 4.1$</td>
<td>158.83</td>
<td>153.67</td>
<td>-3</td>
</tr>
</tbody>
</table>

Table 15: Comparison of IVL of SERIANEX deterministic scenarios with my model. Deviations with respect to SERIANEX results are indicated in percent.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>SERIANEX # buildings in DG1</th>
<th>This Thesis # buildings in DG1</th>
<th>Deviation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_w = 3.2$</td>
<td>296</td>
<td>292</td>
<td>-1</td>
</tr>
<tr>
<td>$M_w = 3.7$</td>
<td>1458</td>
<td>1420</td>
<td>-3</td>
</tr>
<tr>
<td>$M_w = 4.1$</td>
<td>3905</td>
<td>3740</td>
<td>-4</td>
</tr>
</tbody>
</table>

Table 16: Comparison of numbers of houses in EMS-98 Damage Grade 1 (DG1) of SERIANEX deterministic scenarios with my model. Deviations with respect to SERIANEX results are indicated in percent.
4. Result comparison with SERIANEX risk study

4.2.3 Comparision using alternative IPEs

Ground-motion prediction is a very critical and dominant factor for seismic hazard and risk assessments (Cornell, 1968; Giardini, 1999), as mentioned already in chapter 2.2.2 about local ground shaking estimation. SERIANEX risk study solely uses the ECOS-02 attenuation law. However, the SED published two successor laws [Álvarez-Rubio et al., 2011; Fäh et al., 2011] for Switzerland. There were also attempts to check the validity of global GMPEs for geothermal applications [Douglas et al., 2012]; Allen-2012 turned out to be accurate (a detailed presentation of all mentioned IPEs can be found in chapter 2.2.2). Using this new knowledge, the developed model was replenished by these IPEs and also compared with the SERIANEX data points.

A graphical result overview can be found in Figure 26; Table 17 and Table 18 compare the results of all IPEs with the reference points both in terms of IVL and number of buildings of damage grade 1. ECOS-02 and Allen-2012 results turn out to be very similar. Obviously also the deviation of Allen-2012 calculations do not deviate dramatically from the SERIANEX data points. Allen-2012 delivers underestimations for the Mw 3.2 case (+4% for IVL/-10% for DG1), but overestimations for Mw 3.7 (+9%/+1%) and Mw 4.1 (+20%/+6%) while a tendency of slightly increasing overestimation can be made with increasing magnitude. The observations are valid for both the IVL and damage grade domain. ECOS-02 revised and ECOS-09 results lie close together too. This seems to be logical, since ECOS-02 revised is an advanced version of ECOS-02 attenuation law which was made in the course of ECOS-09 development. However, both models using this two IPEs give underestimations compared with the two data points Mw 3.2 and 3.7. Considering the Mw 4.1 event, ECOS-02 revised gives even a slight overestimation while ECOS-09 still lies under the SERIANEX data point.

Considering the Mw 3.2 where the ECOS-02 model delivers a IVL of 10.46 Mio. CHF where ECOS-09 calculates a IVL of 4.75 Mio. CHF (this is a difference of 5.71 Mio. CHF or around 55% less with respect to ECOS-02) it can be seen clearly that IPEs can significantly influence loss calculations.

4.2.3.1 Including Site Amplifications

Since site amplification maps are available and cover whole Switzerland, they were integrated into the model used in this thesis. Site amplifications specifically were calculated for ECOS-02 and ECOS-09 attenuation laws (see chapter 2.2.2.7). For ECOS-02 revised and Allen-2012 the values as calculated for ECOS-02 were taken. Since Allen-2012 and ECOS-02 calculations deliver similar results, this application can be partly justified. In the case of ECOS-02 revised, the decision was made arbitrarily. To be sure, complete adaptations of the site amplifications need to be made for the respective attenuation laws.

Calculation results compared with the three SERIANEX data points are presented in Figure 27, Table 19 and Table 20. Basically it can be observed that all models compute higher IVL values than without site amplifications. ECOS-02 and Allen-2012 still stick close together. Compared to ECOS-02, ECOS-02 revised values are much smaller for low-magnitude cases, where they lie close together in the high-magnitude range. One need to keep in mind that ECOS-02 revised site amplifications are not really justified! However, ECOS-09 IVL values almost fit the SERIANEX data points (deviations between -17 and +2.5%).

Since SERIANEX did not use site amplifications, this direct comparison of the presented results should be treated carefully.
Figure 26: Deterministic loss curve for the IPEs ECOS-02, ECOS-02 revised, ECOS-09 and Allen-2012: Insured Value Loss (IVL) vs. Magnitude $M_w$. The most plausible results and deterministic scenarios carried out by the SERIANEX risk study for the Magnitude events $M_w = 3.2$, $M_w = 3.7$ and $M_w = 4.1$ are included. Site amplifications were not applied.

Table 17: Comparison of IVL of SERIANEX deterministic scenarios with my model. Considered are different IPEs: ECOS-02, ECOS-02 revised, ECOS-09 and Allen-2012. Deviations with respect to SERIANEX results are indicated in percent. Site amplifications were not applied.

<table>
<thead>
<tr>
<th>model</th>
<th>$M_w = 3.2$</th>
<th></th>
<th>$M_w = 3.7$</th>
<th></th>
<th>$M_w = 4.1$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SERIANEX</td>
<td>10.52</td>
<td>-1</td>
<td>53.95</td>
<td>-2</td>
<td>158.83</td>
<td>-3</td>
</tr>
<tr>
<td>ECOS-02</td>
<td>10.46</td>
<td>-1</td>
<td>52.80</td>
<td>-2</td>
<td>153.67</td>
<td>-3</td>
</tr>
<tr>
<td>ECOS-02 rev.</td>
<td>5.66</td>
<td>-46</td>
<td>46.02</td>
<td>-15</td>
<td>166.81</td>
<td>+5</td>
</tr>
<tr>
<td>ECOS-09</td>
<td>4.75</td>
<td>-55</td>
<td>33.54</td>
<td>-38</td>
<td>111.07</td>
<td>-30</td>
</tr>
<tr>
<td>Allen 2012</td>
<td>10.14</td>
<td>-4</td>
<td>58.62</td>
<td>+9</td>
<td>189.95</td>
<td>+20</td>
</tr>
</tbody>
</table>

Table 18: Comparison of numbers of houses in EMS-98 Damage Grade 1 (DG1) of SERIANEX deterministic scenarios with my model. Considered are different IPEs: ECOS-02, ECOS-02 revised, ECOS-09 and Allen-2012. Deviations with respect to SERIANEX results are indicated in percent. Site amplifications were not applied.

<table>
<thead>
<tr>
<th>model</th>
<th>$M_w = 3.2$</th>
<th></th>
<th>$M_w = 3.7$</th>
<th></th>
<th>$M_w = 4.1$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># buildings in DG1</td>
<td>deviation [%]</td>
<td># buildings in DG1</td>
<td>deviation [%]</td>
<td># buildings in DG1</td>
<td>deviation [%]</td>
</tr>
<tr>
<td>SERIANEX</td>
<td>296</td>
<td>-1</td>
<td>1458</td>
<td>-3</td>
<td>3905</td>
<td>-4</td>
</tr>
<tr>
<td>ECOS-02</td>
<td>292</td>
<td>-1</td>
<td>1420</td>
<td>-3</td>
<td>3740</td>
<td>-4</td>
</tr>
<tr>
<td>ECOS-02 rev.</td>
<td>158</td>
<td>-47</td>
<td>1240</td>
<td>-15</td>
<td>4020</td>
<td>+3</td>
</tr>
<tr>
<td>ECOS-09</td>
<td>129</td>
<td>-56</td>
<td>899</td>
<td>-38</td>
<td>2750</td>
<td>-30</td>
</tr>
<tr>
<td>Allen 2012</td>
<td>267</td>
<td>-10</td>
<td>1470</td>
<td>+1</td>
<td>4140</td>
<td>+6</td>
</tr>
</tbody>
</table>
4. Result comparison with SERIANEX risk study

Figure 27: Deterministic loss curve for the GMPEs ECOS-02, ECOS-02 revised, ECOS-09 and Allen-2012: Insured Value Loss (IVL) vs. Magnitude $M_w$. The most plausible results and deterministic scenarios carried out by the SERIANEX risk study for the Magnitude events $M_w = 3.2$, $M_w = 3.7$ and $M_w = 4.1$ are included. Site amplifications were applied.

Table 19: Comparison of IVL of SERIANEX deterministic scenarios with my model. Considered are different IPEs: ECOS-02, ECOS-02 revised, ECOS-09 and Allen-2012. Deviations with respect to SERIANEX results are indicated in percent. Site amplifications were applied.

<table>
<thead>
<tr>
<th>Model</th>
<th>$M_w = 3.2$</th>
<th>$M_w = 3.7$</th>
<th>$M_w = 4.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IVL (Mio. CHF)</td>
<td>deviation [%]</td>
<td>IVL (Mio. CHF)</td>
</tr>
<tr>
<td>SERIANEX</td>
<td>10.52</td>
<td></td>
<td>53.94</td>
</tr>
<tr>
<td>ECOS-02</td>
<td>34.2</td>
<td>+225</td>
<td>135.32</td>
</tr>
<tr>
<td>ECOS-02 rev.</td>
<td>21.5</td>
<td>+104</td>
<td>119.46</td>
</tr>
<tr>
<td>ECOS-09</td>
<td>8.95</td>
<td>-15</td>
<td>51.67</td>
</tr>
<tr>
<td>Allen 2012</td>
<td>32.08</td>
<td>+205</td>
<td>148.14</td>
</tr>
</tbody>
</table>

Table 20: Comparison of numbers of houses in EMS-98 Damage Grade 1 (DG1) of SERIANEX deterministic scenarios with my model. Considered are different IPEs: ECOS-02, ECOS-02 revised, ECOS-09 and Allen-2012. Deviations with respect to SERIANEX results are indicated in percent. Site amplifications were applied.

<table>
<thead>
<tr>
<th>Model</th>
<th>$M_w = 3.2$</th>
<th>$M_w = 3.7$</th>
<th>$M_w = 4.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># buildings in DG1</td>
<td>deviation [%]</td>
<td># buildings in DG1</td>
</tr>
<tr>
<td>SERIANEX</td>
<td>296</td>
<td></td>
<td>1458</td>
</tr>
<tr>
<td>ECOS-02</td>
<td>928</td>
<td>+213</td>
<td>3310</td>
</tr>
<tr>
<td>ECOS-02 rev.</td>
<td>591</td>
<td>+100</td>
<td>2970</td>
</tr>
<tr>
<td>ECOS-09</td>
<td>246</td>
<td>-17</td>
<td>1370</td>
</tr>
<tr>
<td>Allen 2012</td>
<td>824</td>
<td>+178</td>
<td>3340</td>
</tr>
</tbody>
</table>
4. Result comparison with SERIANEX risk study

4.3 Probabilistic Results

Based on a 12-day stimulation period, SERIANEX risk study made a probabilistic risk calculation for the most probable insured value loss (MPIVL, see chapter 2.5). As a result, a MPIVL of around 45 Mio. CHF came out. Reproduction attempts in this study were very difficult, since SERIANEX does not exactly indicate whether $M_{\text{max}}$ of $M_w$ 3.7 or 4.1 was used. Further, they simulated a 12-day stimulation period, while the hazard input for this study takes the real observed data during the Basel EGS project. This real data consists of the seismicity of 6 days stimulation and 6 days after the borehole shut-in. However, in this study a MPIVL of 30.1 Mio. CHF was computed. This value lies very clear (15 Mio. CHF) under the calculated value of computed by SERIANEX. Nevertheless, this deviation can be well explained by the different seismicity input and the uncertainties about the used $M_{\text{max}}$.

SERIANEX risk study also considered probabilistic scenarios for houses of distinct vulnerability indexes and distances to the borehole. Attempts were made to reproduce these results, but failed. The reason behind is the lack of a detailed indication in SERIANEX which $M_{\text{max}}$ where used. Reproductions that come close assume very high $M_{\text{max}}$ of up to $M_w$ 10 which are unlikely to occur in the geothermal context. Therefore, a detailed presentation is avoided.
5. Model Calibration

5.1 General

As mentioned in the previous chapter, it was possible to compute very similar results as in the SERIANEX risk study. This verifies the correctness of the developed loss estimation tool, especially its methodology. Since we know that the real payouts were very generous and exceed real damages, a model calibration to come closer to reality is necessary. Through personal communication with Dr. Peter Meier from Geo-Energie Suisse it is known, that the real financial loss was around 3 Mio. CHF. In my calibration, I use this value as a calibration point. Since this is the only data point available, it must be stated in advance, that the model needs to be recalibrated as soon as new information from future EGS projects are available.

Calibrating the developed model means modifying input and loss estimation modules to influence the output. The output can be expressed in terms of Insured Value Loss, number of houses in distinct damage degrees or casualties. Input changes can just be made by new investigation of the building stock or the insured values. Since this would be out of the scope of this Master thesis, it is not made here. The second option is to analyse the flow chart – in that case for deterministic loss calculation (Figure 28). Four modules influence the output: the choice of IPE, damage estimation, damage grade distribution and the cost function – while the cost function just influences the IVL output. In the course of SERIANEX results comparison (chapter 4) three alternative IPE were introduced additionally to ECOS-02. Since attenuation laws are well established and peer-reviewed, they can’t be directly calibrated. Calibration will be made in the damage estimation module (e.g., damage is not accepted to occur below a certain MMI) and in the cost function. The next chapters deal exactly with these issues.

Since site amplifications are available, they will be integrated from now on in the loss estimation model. The calibration process also includes site amplifications for all presented results.

Figure 28: Flowchart for deterministic loss calculations. Chapters with detailed description of the methodologies are indicated. Modules that will be calibrated are marked.
5.2 Selection of Intensity Prediction Equations

Among the four attenuation laws considered in this study, three are especially designed for Switzerland. The focus lies on ECOS-09, since it is the most recent local IPE available. To provide also an alternative, Allen-2012 is selected too. It provides a global valid law which was also considered to be suitable for the geothermal application [Douglas et al., 2012]. Figure 29 shows the two selected models, applying IPEs ECOS-09 and Allen-2012. It is evident, that both models lie far above the new reference point of 3 Mio. CHF for a $M_w$ 3.2 event.

Further it can be observed in Figure 29 that the ECOS-09 model result lies clearly below Allen-2012 values. To explore the reasons for this, maps with the spatial intensity distribution for both attenuation laws for a $M_w$ 3.2 event were plotted (Figure 30 and Figure 31). Generally Allen-2012 delivers slightly higher intensity values than ECOS-09 does. Especially in the city of Basel even MMI $> 4.5$ are computed. Since a change of attenuation laws would be out of the scope of this thesis, the calibration must be done within both the damage estimation and the cost function.
5. Model Calibration

Figure 30: **ECOS-09** applied: Spatial intensity (MMI) distribution for a $M_w$ 3.2 event.

Figure 31: **Allen-2012** applied: Spatial intensity (MMI) distribution for a $M_w$ 3.2 event.
5.3 Damage Estimation Calibration

5.3.1 General

According to the EMS-98 no damage occurs to structures for MMI < 4. Damage grade 1 appears first for MMI 5 and above (Table 21). SERIANEX risk study modified the mean damage grade calculation (compare chapter 2.3.3) that no damage is allowed to occur for MMI < 3. Being consistent with the EMS-98, no damage for MMI < 4 should be allowed. Since GMPEs do not deliver discrete integer values in terms of MMI, there is obviously some discrepancy with the EMS-98 descriptions. Therefore two new reduction factors are suggested and tested, using the same methodology as described in chapter 2.3.3: One that does not allow damage for MMI < 3.5 and one that doesn’t for MMI < 4 (Figure 32).

Tests applying both reduction factors to ECOS-09 and Allen-2012 models clearly showed that for ECOS-09 the “no damage for MMI < 3.5” option needs to be applied while for Allen-2012 “no damage for MMI < 4” needs to be used in order to fit the reference point of 3 Mio. CHF at Mw 3.2. Figure 33 and Figure 35 illustrate the chosen reduction factors applied to the loss models. As a comparison the computation with the initial reduction factor is shown too. To underline, that the reduction of IVL basically results from less damaged buildings, Figure 34 and Figure 36 plot the number of buildings in damage grade 1.

<table>
<thead>
<tr>
<th>MMI</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>no damage</td>
</tr>
<tr>
<td>II</td>
<td>no damage</td>
</tr>
<tr>
<td>III</td>
<td>no damage</td>
</tr>
<tr>
<td>IV</td>
<td>no damage</td>
</tr>
<tr>
<td>V</td>
<td>Damage grade 1 to a few buildings of vulnerability class A and B (compare Figure 21)</td>
</tr>
</tbody>
</table>

Table 21: extract of EMS-98 [Grünthal, 1998]: Damage to buildings for selected MMI.

![Reduction Factor for Mean Damage Degree](image-url)

*Figure 32: Reduction Factors for the Mean Damage Degree: no damage for MMI < 3 (SERIANEX approach), MMI < 3.5 and MMI < 4 (new suggestions).*
5. Model Calibration

5.3.2 ECOS-09 after reduction factor calibration

The application of a reduction factor that does not allow any damage below MMI 3.5 to the ECOS-09 model performs a good match to the new reference point Figure 33. No damage or no IVL can be observed below $M_w$ 2.8, below $M_w$ 3 just small damage is observed. Figure 34 gives a different view on facts, but with the same statement: For the $M_w$ 3.2 event the number of buildings in DG1 could be reduced from 246 to 75. No buildings are in DG2 to DG5 which confirms EMS-98 descriptions. Since there are no damaged buildings below $M_w$ 2.8, the IVL is zero as well (see Figure 34). For both $M_w$ 2.9 and $M_w$ 3.0 scenarios there are just 3 respectively 13 buildings in DG1.

Figure 33: Deterministic loss curve (IVL vs. $M_w$) applying ECOS-09 attenuation law. Selected reduction factor was applied (solid line); as comparison the model with the initial reduction factor (no damage for MMI <3) is shown too (dotted line). Solid lines represent the most plausible results ($V_0$), dotted lines stand for lower and upper plausible boundaries ($V_+/-$).

Figure 34: Both plots show results before and after application of the new reduction factor (no damage < MMI 3.5), applying ECOS-09 attenuation law. Left: Number of houses in DG1 – DG5 is shown for a $M_w$ 3.2 event. Right: Number of houses in DG1 for $M_w$ up to 3.2.
5.3.3 Allen-2012 after reduction factor calibration

In the case of the Allen-2012 attenuation law the applied reduction factor (no damage below MMI < 4) does not lead to a good fit to the reference point (Figure 35). Nevertheless, the number of buildings in DG1 have been reduced from 824 to 171 (Figure 36) for a $M_w$ 3.2 event. Further the estimated 5 buildings in DG2 (structural damage to a few buildings) have been reduced to 0 after applying the reduction factor. Similar as for the ECOS-09 model, it can also be seen that any kind of loss is absent below $M_w$ 2.8. To finally fit the model to the reference point, the last module, the cost function, will be calibrated. This will influence just the financial losses but not the number of damaged buildings.

![Figure 35: Deterministic loss curve (IVL vs. $M_w$) applying Allen-2012 attenuation law. Selected reduction factor was applied; as comparison the model with the initial reduction factor (no damage for MMI <3) is shown too. Solid lines represent the most plausible results ($V_o$), dotted lines stand for lower and upper plausible boundaries ($V/V_+$).](image)

![Figure 36: Both plots show results before and after application of the new reduction factor (no damage < MMI 4), applying Allen-2012 attenuation law. Left: Number of houses in DG1 – DG5 is shown for a $M_w$ 3.2 event. Right: Number of houses in DG1 for $M_w$ up to 3.2.](image)
5.4 Cost Function Calibration

To finally fit the Allen-2012 model to the reference point the cost function is calibrated. This is done by a very simple approach: The IVL of 3 Mio. CHF is divided by 171 buildings (in DG1 for the $M_w$ 3.2) event. This leads to a loss of around 17'500 CHF per building. Taking the average insured value of all the buildings in DG1 for this scenario (around 1.8 Mio. CHF), the new mean damage ratio (MDR) for DG1 can be estimated. This leads to a MDR of approximately 0.9% for DG1. MDR for DG2 to DG5 cannot be calibrated because there is a lack of datapoints. As a consequence SERIANEX expert judgment values are kept. Table 22 shows the introduced calibrated cost function in comparison with the cost function used in SERIANEX risk study and the average curve from Cochrane and Shaad (1992). The calibrated cost function applied to the Allen-2012 (damage estimation calibration included) shows a good match to the reference point (Figure 37) and will be used for further calculations.

<table>
<thead>
<tr>
<th>Damage Grade (DG)</th>
<th>Cost function / MDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>calibrated cost function for Allen-2012</td>
<td>DG0</td>
</tr>
<tr>
<td>calibrated on Basel Data</td>
<td>0 %</td>
</tr>
<tr>
<td>SERIANEX expert judgment cost function</td>
<td>0 %</td>
</tr>
<tr>
<td>SERIANEX average cost function derived from Cochrane and Shaad [1992]</td>
<td>0 %</td>
</tr>
</tbody>
</table>

Table 22: Calibrated Mean Damage Ratio (ISRA cost function) in comparison with SERIANEX expert judgement curve and the SERIANEX average curve from Cochrane and Shaad (1992).

Figure 37: Deterministic loss curve (IVL vs. $M_w$) applying Allen-2012 attenuation law. The plot compares non-calibrated (red) and calibrated cost function (orange). Solid lines represent the most plausible results ($V_0$), dotted lines stand for lower and upper plausible boundaries ($V_+/V_-$.):
5.5 Final Calibration Results

The final calibrated models ECOS-09 (mean damage grade calibration) and Allen-2012 (mean damage grade and cost function calibration) are compared in Figure 38. Both perform very similar in the range of $M_w$ 2.9 to 3.5. Allen-2012 delivers slightly higher values as ECOS-09 and definitely breaks out above $M_w$ 3.5 (which is of lower interest for the case of EGS projects). Figure 39 shows the number of damaged buildings in DG1 and for all DG (1-5) for the $M_w$ 3.2 case. It can be observed, that Allen-2012 almost over the whole range of plotted magnitudes delivers higher numbers than ECOS-09. Figure 40 and Figure 41 additionally show the regional distribution of buildings in DG1. A circle limiting the influence of damage for a $M_w$ can be set with a radius of around 6 km with it’s center at the borehole.

Figure 38: Deterministic loss curve (IVL vs. $M_w$) for both the calibrated models using attenuation laws ECOS-09 (blue) and Allen-2012 (orange). Solid lines represent the most plausible results ($V_o$), dotted lines stand for lower and upper plausible boundaries ($V_{/V+}$).

Figure 39: Calibrated models for ECOS-09 and Allen-2012 attenuation laws in direct comparison. Left: Number of houses in DG1 – DG5 is shown for a $M_w$ 3.2 event. Right: Number of houses in DG1 for $M_w$ up to 3.2.
Figure 40: Geographical distribution of houses in DG1 for the calibrated ECOS-09 model. Computations were made for a $M_w 3.2$ event. The circle in red indicates the radius which encloses the building stock taken into account, the blue circle shows the radius within damages occur.

Figure 41: Similar plot as Figure 39, but for the Allen-2012 model.
6. Probabilistic Results with Calibrated Models

6.1 General

In the previous chapter the models using ECOS-09 and Allen-2012 were selected and calibrated. Model calibration was based on the estimated real financial loss due to IS released in the context of the Basel EGS in 2006. This chapter presents the integration of the two calibrated deterministic models with the forecast model that computes the seismic hazard (methodology see chapters 2.2.1 and 2.4).

The forecast model uses data recorded during the Basel EGS sequence. This sequence contains both records of the stimulation period as well as records after the shut-in. For future EGS projects the development of new traffic light systems is of major interest. Such alert systems contribute to the control of injections. Therefore, computations are limited to the 6-day stimulation period between the 2nd and 8th December 2006 (see chapter 1.2). The Probabilistic Loss Curves (PLC) is presented in this chapter focuses on two time windows:

1) the entire 6-day stimulation period
2) 1 day within the stimulation period (mean of the entire 6-day period)

All PLC include models considering the different maximum magnitudes \( M_{\text{max}} \) of \( M_w \) 3.7, 5 and 7. \( M_{\text{max}} \). The \( M_{\text{max}} \) values were chosen in accordance with values considered in Mena et al. [2012]. The plots show exceedance probabilities as a function of loss in terms of IVL and number of houses in DG1.

6.2 Risk for the entire 6 days of stimulation

In this section the risk for the 6-day stimulation period is computed. Figure 42 illustrates exceedance probabilities as a function of IVL in CHF, Figure 43 as a function of number of houses in DG1.

6.2.1 ECOS-09 and Allen-2012 model comparison

Comparing the two models, it can be observed that ECOS-09 generally computes higher probabilities for the same IVL (below \( 4 \times 10^8 \) CHF) as Allen-2012 does (Figure 42). Looking at Figure 43, a different observation can be made: Probabilities for the same number of houses in DG1 do not differ that much. Higher results for ECOS-09 are even limited to a range of very low loss (up to \(~150 – 200\) houses). For larger loss Allen-2012 consequently computes higher probabilities. The reason behind this discrepancy between the PLCs expressed in IVL and number of damaged houses in DG1 is to be found in a deterministic analysis. Figure 39 of the previous chapter illustrates damaged houses as a function of \( M_w \). The Allen-2012 estimates for all magnitude scenarios almost double the amount of houses compared to ECOS-09. Considering that for the Allen-2012 a cost function calibration was performed to equalize this effect, reasons become clear. While the deterministic loss curves (expressed in IVL) for both Allen-2012 and ECOS-09 compute very similar results (Figure 38), the integration with the seismic hazard forecast model indicate the effect of the two different attenuation laws. They clearly have an impact on the seismic hazard computation and therefore differences can be observed in the PLCs. Differences in the deterministic loss models expressed in number of damaged houses are equalized in the PLCs by the described impact of IPEs on the hazard calculation.
6. Probabilistic Results with Calibrated Models

6.2.2 Influence of M\(_{\text{max}}\)

It is evident that if higher M\(_{\text{max}}\) are considered, exceedance probabilities for higher magnitude events are automatically higher. This can be seen clearly in both Figure 42 and Figure 43. Since exceeding probabilities are plotted vs. IVL - respectively number of houses in DG1 - exceeding probabilities for high values of these quantities are higher when considering M\(_{\text{max}}\) 5 or 7 instead of 3.7.

To determine the impact of different M\(_{\text{max}}\) on low loss values, a selection of exceedence probabilities (0.1, 0.6 and 0.9) with their associated loss is presented in Table 23. The expected loss for the different M\(_{\text{max}}\) 3.7, 5 and 7 can be compared. It can be seen, that there are differences in loss comparing M\(_{\text{max}}\) 3.7 to M\(_{\text{max}}\) 5 and 7, but losses for M\(_{\text{max}}\) 5 and 7 are identical. The differences between loss values related to M\(_{\text{max}}\) 3.7 compared to M\(_{\text{max}}\) 5 and 7 increases for lower probabilities respectively higher loss. Consequently, the choice of M\(_{\text{max}}\) influenced also the lower loss range which is important for risk assessment in the geothermal context.

<table>
<thead>
<tr>
<th>Exceedance Probability</th>
<th>M(_{\text{max}})</th>
<th>IVL (Mio. CHF)</th>
<th># buildings in DG1</th>
<th>IVL (Mio. CHF)</th>
<th># buildings in DG1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>3.7</td>
<td>1.42</td>
<td>39</td>
<td>0.33</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2.3</td>
<td>63</td>
<td>0.7</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>2.3</td>
<td>63</td>
<td>0.7</td>
<td>42</td>
</tr>
<tr>
<td>0.6</td>
<td>3.7</td>
<td>4.4</td>
<td>121</td>
<td>1.8</td>
<td>102</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>8.7</td>
<td>238</td>
<td>4.3</td>
<td>241</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>8.8</td>
<td>240</td>
<td>4.3</td>
<td>243</td>
</tr>
<tr>
<td>0.1</td>
<td>3.7</td>
<td>8.3</td>
<td>227</td>
<td>4.0</td>
<td>227</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>21.6</td>
<td>584</td>
<td>12.5</td>
<td>684</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>21.9</td>
<td>592</td>
<td>12.7</td>
<td>695</td>
</tr>
</tbody>
</table>

Table 23: Loss in terms of IVL and number of houses in DG1 for ECOS-09 and Allen-2012 models for selected exceedance probabilities. Values are shown for M\(_{\text{max}}\) 3.7, 5 and 7.

6.2.3 Casualties

Since casualties are unlikely to occur in the geothermal context, exceeding probabilities are shown in a table. Table 23 shows probabilities of exceeding 1 fatality for the different considered M\(_{\text{max}}\). Again the impact of M\(_{\text{max}}\) as discussed above can be clearly seen. The risk increment between M\(_{\text{max}}\) 3.7 and M\(_{\text{max}}\) 5/7 is enormous. However, the differences between M\(_{\text{max}}\) 5 and 7 are negligible. Casualty estimations are based on the number of damaged houses and their damage degrees. Consequently the higher probabilities for Allen-2012 in case of M\(_{\text{max}}\) 3.7 can be explained by the larger number of damaged houses compared to ECOS-09. For comparison: The probability to die in a traffic accident in Switzerland within a time period of 6 days is 6.7E-7 [BfS, 2012].

<table>
<thead>
<tr>
<th>model</th>
<th>exceedance probability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M(_{\text{max}}) 3.7</td>
</tr>
<tr>
<td>ECOS-09</td>
<td>7.0E-12</td>
</tr>
<tr>
<td>Allen-2012</td>
<td>2.5E-07</td>
</tr>
</tbody>
</table>

Table 24: Probability of exceeding 1 fatality. Values are given for different M\(_{\text{max}}\).
6. Probabilistic Results with Calibrated Models

Figure 42: Probabilistic Loss Curve for the 6-days stimulation period during the EGS Basel project. Exceeding probability is plotted vs. Insured Value Loss IVL in CHF.

Figure 43: Probabilistic Loss Curve for the 6-days stimulation period during the EGS Basel project. Exceeding probability is plotted vs. number of buildings in DG1.
6.3 Risk for 1 average day during the stimulation period

Time-dependent risk which can be used as input for e.g. a traffic light system needs to be computed daily and not for an entire period. Decision-makers in charge of the injection regime during a stimulation need up to date information about the risk. To illustrate the daily risk, in this section 1 average day during the stimulation period (6-days long) is shown. In the case of a traffic light system for example, the PLCs can be computed daily or even at shorter time steps.

Figure 44 and Figure 45 illustrate the risk for 1 average day within the 6-day stimulation period. The risk at only 1 day within the entire stimulation period is not as high as for the entire stimulation period. Since most of the findings described in chapter 6.2 are repetitive for PLCs in this section, a detailed result observation is obvious.

Analogue to the PLCs in the previous chapter, probabilities of exceedance for loss expressed in IVL are shown in Figure 44, the risk expressed in terms of number of damaged houses in DG1 is illustrated in Figure 45. Table 25 is analogue to Table 23; it computes the expected loss considering different exceedence probabilities (0.1, 0.6 and 0.9). Obviously, they are much lower compared to the whole stimulation period: losses for an exceedance probability of 0.9 are 0, for 0.6 almost 0. At an exceedance probability of 0.1, the ECOS-09 model computes an IVL of 0.8 (M_max 3.7) and 1.2 Mio. CHF (M_max 5 and 7), while losses are still very low for the Allen-2012 model.

<table>
<thead>
<tr>
<th>Exceedance Probability</th>
<th>M_max</th>
<th>ECOS-09</th>
<th>Allen-2012</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>IVL (Mio. CHF)</td>
<td># buildings in DG1</td>
</tr>
<tr>
<td>0.9</td>
<td>3.7</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>0.6</td>
<td>3.7</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.1</td>
<td>3</td>
</tr>
<tr>
<td>0.1</td>
<td>3.7</td>
<td>0.8</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.2</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>1.2</td>
<td>32</td>
</tr>
</tbody>
</table>

Table 25: Loss in terms of IVL and number of houses in DG1 for ECOS-09 and Allen-2012 models for selected exceedance probabilities. Values are shown for M_max 3.7, 5 and 7.

Observations of probabilities for exceeding 1 fatality (Table 26) result in similar findings as observed for the entire 6-day stimulation period. Probabilities for all M_max are significantly lower as the values computed in chapter 6.3. The probability of dying in a traffic accident in Switzerland for only 1 day is 1.1E-7. The risk (for 1 day) to suffer insuries due to a traffic accident (including slight/heavy injuries and death) is 8.2E-6 [BfS, 2012].

<table>
<thead>
<tr>
<th>exceedance probability for 1 fatality</th>
</tr>
</thead>
<tbody>
<tr>
<td>model</td>
</tr>
<tr>
<td>ECOS-09</td>
</tr>
<tr>
<td>Allen-2012</td>
</tr>
</tbody>
</table>

Table 26: Probability of exceeding 1 fatality. Values are given for different M_max.
6. Probabilistic Results with Calibrated Models

Figure 44: Probabilistic Loss curve for 1 day in the 6-days stimulation period during the EGS Basel project. Exceeding probability is plotted vs. Insured Value Loss IVL in CHF.

Figure 45: Probabilistic Loss curve for 1 day in the 6-days stimulation period during the EGS Basel project. Exceeding probability is plotted vs. number of buildings in DG1.
7. Case Study: Impact of Distance and Site Amplifications

7.1 Set-up

Since in 2006 small earthquakes in the context of the EGS project in Basel caused minor damages to structures, the impact of IS to buildings caused by reservoir stimulation remains one of the lingering questions for future EGS projects in Switzerland. Insurance pay-outs after the Basel 2006 events were very generous. It is assumed, that many reported damages to buildings were not due to the earthquakes caused by the EGS project (compare chapter 4.1). Considering new possible sites for future EGS projects, it may be of importance to get an idea in advance, what the spatial impact of IS to settlements could be.

To explore the influence of IS, the building stock of a medium-sized Swiss city ("synthetic city"), presented in chapter 3.2, is used. This case study uses the ECOS-09 attenuation law with the described methodology including calibration (chapter 5). To demonstrate spatial effects, the distance between the borehole and the synthetic city is varied from 1 to 20 km with 1 km increments (Figure 46).

Since it is known that earthquake ground motion amplifications differ due to subsoil conditions (compare chapter 2.2.2.7) a selection of geological settings is considered. A direct comparison of different site amplifications using the same building stock could show possible influences of subsoil conditions to loss, when considering future EGS sites. In this case study, site amplifications published for ECOS-09 attenuation law [Fäh et al., 2011] are used. A selection of typical underground settings for Swiss cities in the geotectonic regions of the Midland and Jura is considered (defined by analysing Swiss geological maps [swisstopo, 2012]).

Table 27 shows all selected subsoils including site amplification values. Malm/Jura is representing sites in the Swiss Jura. Molasse is found in wide parts of the Swiss midland, while it can be distinguished between lower and upper freshwater molasse (USM/OSM) and lower and upper saltwater molasse (UMM/OMM). Since site amplifications for the different types of molasse just differ slightly, the USM has been selected as a representative. To account for quarternary units, on which many Swiss cities are built, also organic soils, fluvioglacial and glaciolaucric gravels, moraines and big alluvial plains are included. Consulting historical maps, it can be said, that settlements more and more moved onto big alluvial plains.
7. Case Study: Impact of Distance and Site Amplifications

<table>
<thead>
<tr>
<th>geological unit</th>
<th>regional restriction</th>
<th>Amplification [MMI]</th>
</tr>
</thead>
<tbody>
<tr>
<td>mesozoikum</td>
<td>Malm, Jura</td>
<td>-0.01 (0 used)</td>
</tr>
<tr>
<td>tertiary</td>
<td>lower freshwater molasse USM ( Chattien)</td>
<td>0.51 (0.5 used)</td>
</tr>
<tr>
<td></td>
<td>Jura and midland molasse</td>
<td></td>
</tr>
<tr>
<td>quaternary</td>
<td>organic soils</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Fluvio-glacial and glaciolacustric gravels</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Moraines, including recent moraines</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>midland molasses and Jura</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Big alluvial plains</td>
<td>0.75 (assumption!)</td>
</tr>
</tbody>
</table>

Table 27: Typical subsoils in the Swiss midland and Jura were most of the medium- and large-sized cities can be found. (source: Fäh et al. [2011]). Site amplification values are for the ECOS-09 attenuation law.

The value for big alluvial plains remains an assumption – in the context of site amplifications for ECOS-09 attenuation law a value of 0 MMI is published, but, for the ECOS-02 a higher estimate (+1.05 instead of +0.33) is taken (compare chapter 2.2.2.7). Therefore + 0.75 is assumed in the ECOS-09 case. It needs to be kept in mind, that the author of the ECOS-09, where the above values are published, remarks that especially values for the soil classes as organic soils and alluvial plains may be underestimated and should be treated with care. This results from the fact that most calibration points taken to derive these values tend to be situated on the edge of such soil types [Fäh et al., 2011].

7.2 Results

7.2.1 Deterministic Scenario: M_w 3.2

This specific scenario focuses on a M_w 3.2 event, similar to the largest event that happened during the Basel EGS. Earlier in this thesis, results of this scenario were presented based on the Basel building stock (see also chapter 4) with the aim to compute real damages. Since the Basel building stock contains 79 different spatially distributed settlements, a direct link of losses with the distance settlement-geothermal field could not be made. The introduction of this scenario, using the synthetic city data set can better illustrate the impact’s distance-dependency. Additionally, the effect of site amplification can be easily compared.

Figure 47 illustrates losses in terms of IVL vs. distance; Figure 48 expresses losses in number of damaged houses in DG1 vs. distance. Both figures include all chosen site amplifications. Casualties were also calculated. It results that for a M_w 3.2 event zero fatalities occur. Therefore a plot is not shown.

Site amplifications, when small (< +0.5 MMI), turn out to be very crucial in the first 6 km. The differences in loss are – as expected – the larger the closer the geothermal field is (where the earthquake is assumed to happen). At a distance of 0 km, the IVL for a amplification of 0 MMI (Malm, Jura) is 0.13 Mio. CHF, while it is 1.65 Mio. CHF for 0.75 MMI amplification (big alluvial plains), more than 1 order of magnitude higher! Considering the same amplifications at a distance of 10 km the financial loss has reduced to 0.23 Mio. CHF for big alluvial plains and to 0 or close to 0 for all
other site amplifications. At this distance, loss values for small site amplification also lie very close together. The same observations can be made in Figure 48 where loss is expressed as a number of damaged houses in DG1.

Based on the above mentioned observations and Figure 47/Figure 48 one could limit the influence of the geothermal field to 8 – 10 km for all considered geological units and their site amplifications except for big alluvial plains. This may be of importance, considering the issue of the radius of influence, e.g. if the site for an EGS can not be chosen.

A complete other starting point would be when an operator is free to choose the site location: Different thresholds of accepted loss could be defined. If a maximum financial loss of 0.5 Mio. CHF is accepted, the distance borehole-settlement needs to be at least 1 km for a city standing on a moraine (0.35 MMI site amp.), 3.5 km for a city on molasse/organic soils (0.5 MMI site amp.) or 7 km for organic soils (0.75 MMI site amplification). Considering a threshold of 1 Mio. CHF to be accepted for a Mw 3.2 event, the distance of influence just matters if the city stands on a big alluvial plain. In that case the EGS site should be at least 4 km away from the city not to cross the threshold. These two examples are shown in Figure 47. Figure 48 shows similar scenarios, but thresholds in terms of a number of houses (20 and 30).
Figure 47: Insured Value Loss IVL [Mio. CHF] vs. distance synthetic city-borehole. Different site amplifications are considered. Thresholds for 0.5 and 1 Mio. CHF represent minimal distances which should be kept not to exceed the thresholds.

Figure 48: Number of damaged houses in DG1 vs. distance synthetic city-borehole. Different site amplifications are considered. Thresholds for 20 and 30 affected buildings represent minimal distances which should be kept not to exceed the thresholds.
7.2.2 Probabilistic Results: Loss for Specific Exceeding Probabilities

To introduce probabilistic results for the synthetic city case study, the Basel EGS sequence has been taken as input for the hazard calculation. Probabilistic results presented in this section are consequently computed based on the synthetic city building stock but with the hazard input taken from the Basel EGS data. The reasoning behind is simple. By introducing probabilistic plots, thresholds based on exceedance probabilities can be presented. Further the Basel EGS sequence is the only sequence for Switzerland available so far. For all computations presented in this chapter a $M_{\text{max}}$ of 3.7 was chosen.

Figure 49 and Figure 50 illustrate loss in terms of IVL respectively number of damaged houses in DG1 vs. distance settlement – borehole/geothermal field for an exceedance probability of 60%. This means for example: The probability, that a 0.75 Mio. CHF loss is exceeded for the synthetic city on Malm/Jura soil (0 MMI amplification) is 60% (compare Figure 49).

Basically the same observation as for the deterministic scenario of a $M_w$ 3.2 event (see previous chapter) can be made: Site amplifications have larger influence for low distances, while the influence decreases (obviously also due to the IPE) at larger distances. Big alluvial plains are still critical and site amplifications have a large effect on the costs.

Using probabilistic results leads to another way of defining thresholds. One can say, that a risk e.g. 2 Mio. CHF – at an exceedance probability of 60% - should not be exceeded. Based on this statement, the distances how far a EGS project should be away from a mid-sized city, thresholds can be defined. In the case of soils as Malm/Jura, gravels or moraines the threshold is not crossed and consequently the distance city-geothermal field can be neglected. The distance question gains importance when looking at the molasse (USM) and big alluvial plains. Is the synthetic city built on an alluvial plain, a distance of 6.5 km is necessary not to exceed the threshold; for the molasse subsoil condition just a 3 km distance is necessary (compare Figure 49). A similar scenario, using a defined number of damaged houses, is shown in Figure 50.
7. Case Study: Impact of Distance and Site Amplifications

Figure 49: Insured Value Loss (IVL) [Mio. CHF] vs. distance synthetic city–borehole for an exceedance probability of 60%. Different site amplifications are considered. 2 Mio. CHF is taken as non-exceedance threshold.

Figure 50: Number of damaged houses in DG1 vs. distance synthetic city–borehole for an exceedance probability of 60%. Different site amplifications are considered. 60 buildings in DG1 is taken as non-exceedance threshold.
8. Sensitivity Analysis and Model Limitations

8.1 General

To compute a PLC as presented in the previous two chapters, many computation steps are necessary. Each step has a certain influence on the final result. This chapter casts light on the sensitivities of the developed tool. Figure 51 illustrates the developed risk calculation tool as a flowchart to give an overview. Sensitivities of modules such as the choice of IPEs, site amplifications, damage calibration, the cost function and the choice of the maximum magnitude are explored in the next subchapters. Many sensitivities were illustrated already in the past chapters, therefore reference to the corresponding plots are given.

![Flowchart](image)

*Figure 51: Flowchart containing all modules leading to the Probabilistic Loss Curve PLC. Sensitive steps are marked by blue-dotted squares.*

8.2 IPE selection

The selection of an appropriate attenuation law is one of the most critical points in the presented risk calculation tool. The effect of different IPEs in the deterministic domain can be clearly seen in chapter 4.2.3, Figure 26, where four selected attenuation laws are plotted vs. magnitude Mw. This plot, which is not calibrated to any reference point, illustrates that the influence may be enormous. ECOS-09 and Allen-2012 models were selected and calibrated for further computations. Although both models were calibrated in the deterministic domain (which produced very similar results, see Figure 38) differences between them are still clearly recognisable when computing PLCs (see Figure 42 to Figure 45). This influence can be attributed to the fact, that IPEs (which actually were not calibrated itself, see also chapter 5) are used for the hazard calculation as well. Introducing a weighting, taking both IPEs into account, may be an option to cope with this problem.
8. Sensitivity Analysis and Model Limitations

8.3 Site Amplification

The case study based on the “synthetic city” data set presented in chapter 7 took into account different subsoil conditions for the same settlement. The impact of increasing site amplification can be directly compared both in the deterministic (Figure 47 and Figure 48) and probabilistic domain (Figure 49 and Figure 50). A factor of up to 12 can be observed, comparing the deterministic loss models for 0 and 0.75 MMI amplification directly beneath the geothermal field. The importance of site amplifications declines with increasing distance to the borehole, however, this is also coupled with the IPE (the impact of an earthquake decreases with increasing distance to the epicenter, see also chapter 2.2.2).

8.4 Cost Function and Insured Value

In the context of model calibration the cost function has been adapted based on a reference point chapter 5.4. Table 22 lists the changes made in the cost function. Just the damage ratio for buildings in DG1 has been changed. The effect can be seen in Figure 37; as expected the influence of the cost function change is limited to lower magnitude, since damage grades are limited in that case to DG1 (see Figure 19). Even if this example just affects changes in DG1 and consequently lower magnitudes, it can be seen that a change is directly coupled to the output as long as the output is displayed in terms of financial losses.

In this thesis just one cost function for all building classes is used. It originally is the mean of different cost functions for different building classes [Cochrane and Schaad, 1992]. To increase the cost function’s accuracy, functions for each building class should be derived. This requests further in-depth investigation relying on real data which unfortunately is out of the scope of this thesis.

In the same category falls the insured value (IV) per building. For the Basel dataset the mean of the real IV of an entire settlement was taken, in the case of the Yverdon data an IV per building was just assumed. It is evident, that the IV is directly coupled with the final financial loss output of the model and it is therefore one of the most sensitive parameters. A careful selection is necessary and results should be treated extremely carefully, especially when communicated to the public. An alternative and less sensitive output parameter is the number of damaged houses in e.g. DG1, which always is given in this thesis as a second output parameter.

8.5 Maximum Magnitude $M_{\text{max}}$

The maximum possible earthquake $M_{\text{max}}$ considered in ISHA is a crucial parameter [Bachmann et al., 2011]. Differences are well illustrated in the PLCs shown in chapter 6 (Figure 42 to Figure 45). Considering larger $M_{\text{max}}$ increases exceedance probabilities of higher losses. Nevertheless the effect on low loss values remains minor as it can be observed in Figure 42 to Figure 45. Observations can be underlined by analysing the loss for distinct exceedance probabilities (0.1, 0.6 and 0.9) as listed in Table 23. Since there is no consensus in the scientific community about the $M_{\text{max}}$ issue [Mena et al., 2012], it might be fortunate to consider always different $M_{\text{max}}$ when computing ISRA.
8. Sensitivity Analysis and Model Limitations

8.6 Most dominant Magnitude events for probabilistic results

The seismicity rate is an important input parameter for the used seismic hazard forecast model (ISHA). Since this forecast model is directly integrated with the loss calculation, seismicity rates control the PLCs. Figure 52a shows the number of forecasted events per magnitude bin for the 6-day stimulation period of the Basel EGS sequence. The plot considers the magnitude range of $M_w$ 1 – 7 with an increment of 0.1. Approximately 250 events of $M_w$ 1 are forecasted, while for $M_w$ 2 just a computation of 7 results. $M_w$ 3 results in 0.2 events. A rapid decay with increasing magnitude can be observed.

To put the seismicity rates in a context with possible loss values, the IVL (for ECOS-09 and Allen-2012, see Figure 52b) as a function of $M_w$ is multiplied by the seismicity rates (in magnitude bins) and normed to 1 according to equation (8.1).

\[
Pseudo \text{ IVL probability} = IVL \times \text{seismicity rates; normed to 1}
\]

Figure 52c illustrates the result. Since the IVL for both models is zero for $M_w < 2.8$, there is no influence of high seismicity rates in the low magnitude range ($M_w$ 1-2.8). The influence rapidly increases for $M_w > 2.8$. Maximum values are observed at $M_w$ 3.8 for the ECOS-09 model, respectively $M_w$ 4.5 for the Allen-2012 model. The influence decays very rapidly again after the mentioned climaxes. Seismicity rates can explain it: The reason behind can be found in the logarithmic zoom window for larger magnitudes (Figure 52a), where low values above $M_w$ 3 reach very low values down to $10^{-7}$.

Generally the observations lead to the statement, that magnitudes between $M_w$ 3.5 and 5 contribute most to the final risk in the case of Allen-2012, while it can be limited to a range of $M_w$ 3.5 to 4.5 for ECOS-09.
Figure 52: a) Seismicity rates calculated with the combined forecast model in the magnitude domain. b) Insured Value Loss IVL [CHF] for the calibrated models ECOS-09 and Allen-2012 vs. magnitude $M_w$ (deterministic domain). c) Pseudo probability of IVL, normed to 1: It represents the multiplication of a) and b) normed to one for the large values.
9. Inputs for Future Traffic Light Systems

During the stimulation phase of the Basel EGS in 2006 a traffic light system developed by Bommer et al. [2006] was in use in order to control and if necessary abort stimulation. Although the operator company followed the system correctly, for the geothermal scale large earthquakes occurred and caused material damage and public concerns (see also chapter 2.1). One of the major reasons for the public outcry was, that local residents did not feel well and honestly informed by the operator company.

In this chapter I present some inputs for a future traffic light system and a method how the public could be daily informed about the seismic hazard. Therefore the developed and calibrated model is used with the Basel EGS dataset and its recorded seismic sequence in 2006 (see also chapters 5 and 6). A maximum magnitude of Mw 3.7 is considered. ECOS-09 IPE has been used for the calculation.

The idea is simple: Induced seismicity risk is calculated for each day of a 15-day period starting from the first day of stimulation. In advance a certain value of loss is defined. The probability of exceeding this defined loss value is calculated on each day during the selected period. It is to be seen as a forecast for the next 24 hours (the forecast could be refined down to 6 hours). Such a curve illustrates the time-dependent risk. The decision whether injections should be stopped or not would be based on a “probability threshold”. E.g. a probability of exceeding the selected loss value of 10% can be defined (which is absolutely assumptive!), once this threshold is exceeded, injections can be stopped. Figure 53 schematically illustrates the procedure.

The developed risk assessment tool expresses loss in terms of IVL, number of damaged houses in DG1 and casualties. Since casualties are not expected to occur, both examples presented here are limited to the other two output quantities. To provide two examples of a traffic light system introduced above, exceeding probabilities were calculated daily for an IVL of 2 Mio. CHF (Figure 54) and 50 affected buildings in DG1 (Figure 55).

In both Figure 54 and Figure 55 an increasing risk can be observed between day 1 and day 5 of the stimulation phase. The risk is at its maximum between day 5 and 6. Injections were stopped between day 5 and 6, but the risk still remained over 10% of exceeding the defined loss quantities. A decrease can be observed right after the occurrence of the Mw 3.2 event. Assuming an arbitrary threshold of 10% exceedance probability, it can be defined to stop stimulations/injections when this threshold is passed. Since the value of 10% is for illustration purpose only, further investigations are needed to find out at which level the threshold is to be set.
Figure 54: Exceeding probabilities for 2 Mio. CHF IVL during the Basel EGS project in 2006. To illustrate the causal relationship between seismicity and probability of exceeding a certain loss, earthquake events expressed in $M_W$ are shown as a function of time.

Figure 55: Exceeding probabilities for 50 buildings suffering damage grade 1 during the Basel EGS project in 2006. To illustrate the causal relationship between seismicity and probability of exceeding a certain loss, earthquake events expressed in $M_W$ are shown as a function of time.
9. Inputs for Future Traffic Light Systems

Time-dependent risk curves that indicate the risk in terms of exceedance probability (Figure 54 and Figure 55) may not be easy understandable by the public. Further it is doubtful whether expected loss should be communicated in terms of monetary loss, since the output strongly depends on input and the cost function (compare sensitivity analysis in chapter 8.4).

The seismic hazard map for Switzerland for normal earthquakes illustrates the hazard in terms of PGA with a 10% exceedance probability in 50 years [Giardini et al., 2004]. Communication to the public could be done similarly for EGS projects. Since PGA is a rather unknown quantity in the public, the expression in terms of expected MMI is a better option. The scale of MMI is defined in theEMS-98. Described are effects on humans, the nature and to buildings. As an example for time-dependent hazard maps I computed the expected MMI for a 10% exceedance probability for the following days (Table 28):

<table>
<thead>
<tr>
<th>day</th>
<th>course of events</th>
<th>map</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 day after stimulation started</td>
<td>Figure 56</td>
</tr>
<tr>
<td>5</td>
<td>around 1 day before M&lt;sub&gt;x&lt;/sub&gt; 3.2 event, largest risk according to Figure 54</td>
<td>Figure 57</td>
</tr>
<tr>
<td>7</td>
<td>just after M&lt;sub&gt;x&lt;/sub&gt; 3.2 event, stimulation is already stopped</td>
<td>Figure 58</td>
</tr>
<tr>
<td>10</td>
<td>~5 days after stimulation stopped</td>
<td>Figure 59</td>
</tr>
</tbody>
</table>

*Table 28: Selection overview of time-dependent hazard maps. Also compare with Figure 54 and Figure 55.*

As expected, an increased risk of higher intensities to occur can be observed for day 5, just before the M<sub>x</sub> 3.2 event. A decrease of expected intensities is observed after the shut-in and the stop of injections. Such maps could be published daily by the operators of future EGS projects to inform local residents of the expected intensity of ground shaking – this would be like a weather forecast. These maps should be accompanied by a detailed description, what effects on humans and structures are to be expected, as published in the EMS-98, but refined and more specific to local site conditions. A description may contain e.g. photos of possible damages at certain intensity levels as they occured in the context of the Basel EGS.

Still, the communication of possible risk and consequences remains very delicate and should be analyzed in detail. This includes the determination of the assumed exceedance probabilities as well as impact description and – unfortunately – is out of the scope of this thesis. I ask the reader to see the suggestions for future traffic light system as an input which needs to be assessed and defined in detail.
9. Inputs for Future Traffic Light Systems

Figure 56: Expected MMI for 10% exceedance probability at day 1.

Figure 57: Expected MMI for 10% exceedance probability at day 5.
9. Inputs for Future Traffic Light Systems

Figure 58: Expected MMI for 10% exceedance probability at day 7.

Figure 59: Expected MMI for 10% exceedance probability at day 10.
10. Discussion

10.1 General

The reservoir stimulation beneath Basel in 2006 released widely felt earthquakes that even caused slight damages to structures. Concerns of both local residents and public authorities were leading to the final stop of the project. With hindsight the risk of IS and potentially triggered earthquakes was underestimated [Bachmann et al., 2011]. IS and the handling of its associated risk remains one of the main obstacles for future EGS projects in Switzerland and worldwide. In recent years efforts in tackling the issue of IS led to pseudo-prospective models based on the Basel EGS sequence [Bachmann et al., 2011; Mena et al., 2012]. The introduction of time-dependent models that compute ISHA is an important step towards an improvement in forecasting IS.

The ISRA calculation tool developed in this Master thesis combines these seismic hazard forecast models [Mena et al., 2012] with associated loss on the surface. Thus the tool provides the possibility of time-dependent risk assessment for IS (ISRA). By expressing seismic risk in terms of monetary, material and human loss, widely understandable quantities are introduced and may help addressees such as EGS operators, public authorities, local residents and insurances to better understand the risk of IS in the course of future EGS projects.

10.2 Calibration and Sensitivities

In this thesis it has been proved that the developed risk calculation tool is able to achieve very similar results (< 3% deviation) for three magnitude scenarios (Mw 3.2, 3.7 and 4.1) for Basel and its surroundings, assessed in the context of the SERIANEX risk study. Since the risk calculation tool uses a very similar and well-established loss estimation methodology as the before mentioned risk study does, the model gets a certain verification. The almost perfect match of these three data points does not explicitly imply that both the results computed in this thesis and SERIANEX results reflect true loss. It rather demonstrates that the model works flawlessly concerning technical aspects.

The abovementioned computations were all performed with an out-of-date attenuation law (IPE ECOS-02), which needed to be done to compute comparable results with SERIANEX. Selecting ECOS-09 (successor IPE of ECOS-02 and most recent IPE based on Swiss data) and Allen-2012 (IPE based on global data) a selection of attenuation laws that is state of the art and suitable for Switzerland can be provided. Although comparisons with the observed intensities during the Basel EGS justified their application, they are basically not developed for low magnitudes as occurring in IS. Nevertheless, since these attenuation laws are well-established and fitted to calibration events, a further calibration is not possible with the available data. Model calibration needs to be done on other modules.

It is known that payouts of 7-8 Mio. CHF [Baisch et al., 2009] for buildings damaged by reservoir stimulations of the Basel EGS were very generously and contained reported damage not associated to IS (chapter 4.1). A calibration of the risk calculation tool using ECOS-09 and Allen-2012 attenuation laws has been performed on real loss estimates of only 3 Mio. CHF (chapter 5.1). Calibration efforts resulted in an increase of the intensity level necessary to cause damage on structures from MMI 3 to 3.5 and 4 for the ECOS-09 and Allen-2012 model respectively. Additionally the cost function for the Allen-2012 has been slightly adapted. The EMS-98 MMI scale (see Appendix A) defines what damage on structures occurs at which intensity level. Therefore the non-acceptance of damage to occur below the mentioned intensity levels is considered to be justified. Smoothly modifying the damage estimation method is the only way to change the number of affected buildings, without developing a
complete new methodology. Although the calibration enables the model now to match estimates of real payouts, more data points are desirable to increase the model accuracy. Since independent data is not available, a model validation is not possible at this point. Future EGS projects can provide data sets to test and validate the developed model.

The above discussed calibration points out that the cost estimation is a very sensitive parameter when considering financial loss as an output. Since the cost function itself represents the average of different cost functions for different building classes, it is a very simplified approach. To provide a more precise solution, a cost function for each building class used within the EMS-98 is needed to be developed. Future studies on that issue could be based on Basel damage reports. The IV of a single building is another vulnerable point: Computations of IVL link the cost function directly with the IV of a building. Consequently, both parameters can be easily modified. Since IV represents a very delicate information which is difficult to access due to data protection (to protect citizens) and data secrecy (protection by insurance companies), it is hard to assess building stocks accurately. Another point is, that a building standing in the city center can have a higher insurance value than a building situated in a less urban area, although repair costs for e.g. a small fissure commonly observed at buildings after the Basel EGS are similar. One way providing a better cost estimation may be to multiply the number of damaged houses by associated possible repair costs for typically occurring damage grades. Up to date no such studies were conducted, but could be done based on the Basel EGS damage claims and reports.

The outpointed sensitivities in the cost estimation all lead to the conclusion, that the communication of financial loss should be treated with extreme care in any case. Regarding the Basel EGS project it can be devastating for an ongoing project if too high risk costs published and circulate among public authorities and residents. An alternative based on well-established methodologies [Giovinazzi and Lagomarsino, 2004; Lagomarsino and Giovinazzi, 2006] is provided by indicating the number of slightly damaged houses (DG1).

One of the major issues the public was concerned about during the Basel EGS reservoir stimulation was a potential triggering of moderate to large earthquakes [Baisch et al., 2009] such as the devastating earthquake in Basel 1356. In fact, there is no consensus in the scientific community on suitable M_{\text{max}} [Mena et al., 2012]. However, Bachmann et al. [2011] stated that the M_{\text{max}} plays a crucial role in ISHA and consequently also in ISRA. The integration of deterministic loss estimations with forecast models in this thesis illustrated the impact of different M_{\text{max}} on loss as shown in PLCs. Risk increments for M_{\text{max}} 5 and 7 compared to M_{\text{max}} 3.7 are significant in terms of probabilities of exceeding losses of any kind including casualties. Obviously especially higher losses associated with larger magnitude events show higher exceedance probabilities. This certainly has an impact on decision-makers weather the risk of a project is bearable or not. Nevertheless, it has been shown in this thesis, that magnitudes between M_w 3.5 and 5 contribute most to the hazard.

10.3 Output Parameters and Input for New Traffic Light Systems

Basel is seismically one of the most active regions in Switzerland [Giardini et al., 2004]. It can be assumed that sites for future EGS projects will be placed at sites with a lower seismic hazard. One of the key seismological questions when choosing possible new locations for EGS sites are local site amplifications. A case study analysing the response of a synthetic city on different subsoils in the Swiss Midland and Jura to IS impacts showed that many Malm/Jura, fluvio-glacial gravels, moraines and molasse are not as critical as alluvial plains. It turns out that it is recommendable to avoid reservoir stimulation in the vicinity of cities built on big alluvial plains.
Regardless of decisions which will be taken where new EGS projects are realised, the matter of handling and communicating the risk of IS during reservoir stimulation remains one of the lingering questions. With the ISRA tool including robust forecast models, an input for new possible traffic light systems to control injection regimes was presented. It forecasts exceedance probabilities for a certain value of loss (this can be expressed in terms of IVL, number of damaged houses or even casualties). One can define a certain probability threshold not to exceed. If this threshold is exceeded, injections regimes could be stopped. The key problem is to define the exceedance probability threshold. If background seismicity rates are known – and this can be done in advance of an EGS project – the natural risk can be defined and possible threshold can be set in accordance. Future studies need to figure out accurate thresholds, also including other datasets.

This input for possible advanced traffic light systems, which uses the calibrated ISRA tool does not forecasts seismic hazard only, but also seismic risk. It can be expressed in terms of financial loss, number of affected houses or even casualties. Discussing on sensitivities of the implemented cost function and the insured value associated to a building touched the issue already. Different output quantities are more or less suitable for different addressees. Affected by an EGS project are e.g. public authorities, local residents, the operator company and insurances. All of them have different interests. While the operator company and investors are basically interested in a successful project without causing any public outcry or expensive damages (or to limit damages), insurances are mainly interested in potential financial losses and the definition of insurance primes in order to cover the risk. A resident rather wants to have confidence that large earthquakes can be excluded and that his house is not damaged. Public authorities finally need to guarantee that no human loss is suffered and that lifelines are not damaged. Figure 60 schematically illustrates the different output quantities and the mentioned interest groups.

![Figure 60: Schematic overview of current and future output quantities of the ISRA calculation tool and possible interest groups.](image)

On account of these different interest groups, it is necessary to adapt the output of both the traffic light system and risk assessments. Public authorities, interested in avoiding human losses may prefer the probability of exceeding one fatality. The insurance profession is more interested in the IVL. In that case a precise assessment of insured values of possibly affected buildings is possible.

On the other hand, local residents who normally do not have an in-depth technical understanding (this affects seismology as well as reservoir engineering) want to be well informed about possible impacts. Just communicating a simple amount of possible loss is very delicate and may frighten people – uncertainties and consequences were discussed in this chapter. Information to the public should be given rather qualitative than quantitative. The hazard forecast maps (indicating expected MMI)
presented in this thesis could be published e.g. every day like a weather forecast, coming along with a short description and explanation of the scale and associated damages. This could also include photographs of fissures, to illustrate the damage. This communication may give the public an idea of what they have to expect. However, this is just an input and does not solve the problem at its full extend.

The operator company is probably the most demanding interest group. It is the operator company that is in charge of the responsibility for the project, but can also take the most influence on injection regimes. One of the biggest challenges is to find a trade-off between optimal reservoir stimulation and the avoidance of felt or even damaging earthquakes. Number of damaged houses would provide solid information to them. Avoiding free riders claiming damage e.g. for fissures not related to the EGS project is another important topic. The synthetic city case study in this thesis gave a first approach how a possible radius of influence could be assessed. Putting the issue in a regulatory context, Swiss building norms should be taken into account. The Swiss building norm SN 640312a, which regulates the shaking on buildings, expresses thresholds in terms of PGV in mm/s. A further development of the ISRA calculation tool presented in this thesis should include a new output expressed in PGV. A case study, similar to the synthetic city case study presented in chapter 7 could give a feeling about the spatial impact.

As discussed above, different interest groups are interested in a different output of the traffic light system. Weighing up the acceptable risk, different output quantities can be used in. A combination of best and worst case scenarios should be taken into account. This means e.g. to define exceedance probability thresholds for both low and high loss. Nevertheless, the question remains what risk the society is willing to take. Nuclear or hydroelectric power stations for example work very safe today, but still they bear the residual risk of a major accident. This residual risk is accepted by the society, since benefits of accepting it are large enough. In the case of EGS projects the possible triggering of large magnitude events can be seen as the residual risk. It is finally a political discussion which leads to the decision what risk threshold is to define for EGS projects.
11. Conclusion

The ISRA calculation tool presented in this Master thesis successfully combines ISRA with potential surface loss. It is a first step towards time-dependent ISRA. Recomputing deterministic results from the SERIANEX risk study, it was possible to technically verify the ISRA calculation tool. A further calibration of the verified model is now able to give a good estimate on possible loss related to EGS projects when an accurate building stock is available. Using the developed tool, it is possible to quantify losses of cities on different subsoil conditions and assess the risk for future EGS sites. Analysing the Basel EGS sequence, magnitudes between M$_{\text{w}}$ 3.5 and 5 turned out to be dominating the risk. The selection of an accurate IPE, the M$_{\text{max}}$ and possible site amplifications were identified as the most sensitive model input parameters. The cost estimation for damaged building was considered to be delicate. A possible application for the presented ISRA calculation tool has been shown: Inputs for future traffic light systems deliver widely understood output quantities in real-time – suited for different interest groups.

Although the developed ISRA calculation tool is based on well-established loss estimation methodologies and performs well for past events, a refinement of input data and methodology is needed. Recalibrating and replenishing the tool with new data and methods as discussed will increase both model robustness and accuracy. Open questions, such as defining suitable non-exceedance thresholds for the proposed traffic light system inputs need to be answered.
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM</td>
<td>Casualty Matrice</td>
</tr>
<tr>
<td>DG</td>
<td>Damage Grade</td>
</tr>
<tr>
<td>DRM</td>
<td>Damage Rate Matrice</td>
</tr>
<tr>
<td>ECOS</td>
<td>Earthquake Catalogue of Switzerland</td>
</tr>
<tr>
<td>ECOS-02</td>
<td>Earthquake Catalogue of Switzerland, Version 2002, also meant the GMPE for Switzerland published in this context</td>
</tr>
<tr>
<td>ECOS-09</td>
<td>Earthquake Catalogue of Switzerland, Version 2009, also meant the GMPE for Switzerland published in this context</td>
</tr>
<tr>
<td>QLARM</td>
<td>Earthquake Loss Assessment for Response and Mitigation</td>
</tr>
<tr>
<td>EGS</td>
<td>Enhanced Geothermal System</td>
</tr>
<tr>
<td>EMM</td>
<td>European Macroseismic Method</td>
</tr>
<tr>
<td>EMS-98</td>
<td>European Macroseismic Scale 1998</td>
</tr>
<tr>
<td>Allen-2012</td>
<td>global valid GMPE derived by Allen et al., 2012</td>
</tr>
<tr>
<td>GMPE</td>
<td>Ground Motion Prediction Equation</td>
</tr>
<tr>
<td>IS</td>
<td>Induced Seismicity</td>
</tr>
<tr>
<td>ISHA</td>
<td>Induced Seismicity Hazard Assessment</td>
</tr>
<tr>
<td>ISRA</td>
<td>Induced Seismicity Risk Assessment</td>
</tr>
<tr>
<td>IV</td>
<td>Insured Value</td>
</tr>
<tr>
<td>IVL</td>
<td>Insured Value Loss</td>
</tr>
<tr>
<td>IPE</td>
<td>Intensity Prediction Equation</td>
</tr>
<tr>
<td>M&lt;sub&gt;L&lt;/sub&gt;</td>
<td>Local Magnitude</td>
</tr>
<tr>
<td>M&lt;sub&gt;max&lt;/sub&gt;</td>
<td>Maximum possible magnitude (M&lt;sub&gt;a&lt;/sub&gt;) considered</td>
</tr>
<tr>
<td>M&lt;sub&gt;w&lt;/sub&gt;</td>
<td>Moment Magnitude</td>
</tr>
<tr>
<td>MDG</td>
<td>Mean Damage Degree</td>
</tr>
<tr>
<td>MDR</td>
<td>Mean Damage Ratio</td>
</tr>
<tr>
<td>mDRM</td>
<td>modified Damage Rate Matrice</td>
</tr>
<tr>
<td>MMI</td>
<td>Modified Mercalli Intensity defined within EMS-98</td>
</tr>
<tr>
<td>MPIVL</td>
<td>Most Probable Insured Value Loss</td>
</tr>
<tr>
<td>PGA</td>
<td>Peak Ground Velocity</td>
</tr>
<tr>
<td>PLC</td>
<td>Probabilistic Loss Curve</td>
</tr>
<tr>
<td>PSHA</td>
<td>Probabilistic Seismic Hazard Assessment</td>
</tr>
<tr>
<td>PSRA</td>
<td>Probabilistic Seismic Risk Assessment</td>
</tr>
<tr>
<td>STEER</td>
<td>Short-Term Earthquake Risk Assessment</td>
</tr>
<tr>
<td>SED</td>
<td>Swiss Seismological Service, Schweizerischer Erdbebendienst</td>
</tr>
<tr>
<td>SERIANEX</td>
<td>trinational Seismic Risk Analysis Expert Group, risk study concerning the Basel EGS</td>
</tr>
<tr>
<td>SERIANEX risk study</td>
<td>trinational Seismic Risk Analysis Expert Group, risk study concerning the Basel EGS</td>
</tr>
<tr>
<td>V&lt;sub&gt;i&lt;/sub&gt;</td>
<td>Vulnerability Index</td>
</tr>
</tbody>
</table>
References & Literature


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Special thanks to Clotaire Michel for sharing his specialist knowledge about vulnerabilities of buildings with me. Only thanks to his excellent contacts to EPFL it was possible to access the entire Yverdon dataset. Thanks also to P. Lestuzzi from EPFL who provided the dataset.

A very important person throughout my thesis was Thomas van Stiphout. He provided me his loss assessment codes used in his PhD thesis as a starting point – including extensive explanations. It would have been a lot harder to start without his help. Thanks also for the discussion of preliminary results and the constructive inputs.

Furthermore I want to thank Philipp Kästli. He granted me access to many datasets, e.g. site amplifications maps or topographic maps of Switzerland within the SED. Not to forget are the various discussions in which he provided me with background information about many SED publications.

I deeply acknowledge the support of Peter Meier and Falko Bethmann from Geo-Energie Suisse. Thanks to their valuable inputs about the Basel EGS project, it was possible to further extend this Master thesis.

Fabienne, I thank you for all the motivating ice cream breaks (since we don’t drink coffee...). It was a pleasure studying with you.

Nearly last but not least, I want to thank all student fellows for all the support and good times during our Bachelor and Master studies at ETH Zurich.

Finally I owe a very big thank you to Senta for her help and patience, not only during the time of this thesis, also during my whole Bachelor and Master studies.
Appendix

Appendix A: European Macroseismic Intensity Scale 1998
Appendix B: SERIANEX building classes
Appendix C: Input Data Format for ISRA calculation tool
Appendix D: Output Data Format for ISRA calculation tool
Appendix E: ISRA calculation tool flow chart
Appendix A: European Macroseismic Intensity Scale 1998

1. Complete European Macroseismic Intensity Scale 1998

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.</td>
<td>Not felt</td>
</tr>
<tr>
<td>II.</td>
<td>Scarely felt</td>
</tr>
<tr>
<td>III.</td>
<td>Weak</td>
</tr>
<tr>
<td>IV.</td>
<td>Largely observed</td>
</tr>
<tr>
<td>V.</td>
<td>Strong</td>
</tr>
<tr>
<td>VI.</td>
<td>Slightly damaging</td>
</tr>
<tr>
<td>VII.</td>
<td>Damaging</td>
</tr>
<tr>
<td>VIII.</td>
<td>Heavily damaging</td>
</tr>
<tr>
<td>IX.</td>
<td>Destructive</td>
</tr>
<tr>
<td>X.</td>
<td>Very destructive</td>
</tr>
<tr>
<td>XI.</td>
<td>Devastating</td>
</tr>
<tr>
<td>XII.</td>
<td>Completely devastating</td>
</tr>
</tbody>
</table>

2. Description low grade intensities

Arrangement of the scale: a) Effects on humans  
b) Effects on objects and on nature  
c) Damage to buildings

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
</table>
| I.    | a) Not felt, even under the most favourable circumstances.  
b) No effect.  
c) No damage. |
| II.   | a) The tremor is felt only at isolated instances (<1%) of individuals at rest and in a specially receptive position indoors.  
b) No effect.  
c) No damage. |
| III.  | a) The earthquake is felt indoors by a few. People at rest feel a swaying or light trembling.  
b) Hanging objects swing slightly.  
c) No damage. |
| IV.   | a) The earthquake is felt indoors by many and felt outdoors only by very few. A few people are awakened. The level of vibration is not frightening. The vibration is moderate. Observers feel a slight trembling or swaying of the building, room or bed, chair etc.  
b) China, glasses, windows and doors rattle. Hanging objects swing. Light furniture shakes visibly in a few cases. Woodwork creaks in a few cases.  
c) No damage. |
| V.    | a) The earthquake is felt indoors by most, outdoors by few. A few people are frightened and run outdoors. Many sleeping people awake. Observers feel a strong shaking or rocking of the whole building, room or furniture.  
b) Hanging objects swing considerably. China and glasses clatter together. Small, top-heavy and/or precariously supported objects may be shifted or fall down. Doors and windows swing open or shut. In a few cases window panes break. Liquids oscillate and may spill from well-filled containers. Animals indoors may become uneasy.  
c) Damage of grade 1 to a few buildings of vulnerability class A and B. |
Appendix B: SERIANEX building classes

Overview of Building Classes and values of Vulnerability Indexes as they are used in the SERIANEX risk study. Building Classes identical with EMS-98 classes are highlighted in blue. $V_0$ values were defined by SERIANEX [Baisch et al., 2009], while $V_+/-$ and $V_{min}/V_{max}$ were defined by myself in collaboration with Dr. Michel Clotarie, SED. For building classes that coincided with EMS-98 building classes, EMS-98 values were taken.

<table>
<thead>
<tr>
<th>Building Class (BC)</th>
<th>Type of Structure</th>
<th>SERIANEX</th>
<th>EMS-98</th>
<th>$V_{min}$</th>
<th>$V_-$</th>
<th>$V_0$</th>
<th>$V_+$</th>
<th>$V_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MASONRY (M)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>Simple stone with timber slabs</td>
<td>M3</td>
<td></td>
<td>0.46</td>
<td>0.65</td>
<td>0.74</td>
<td>0.83</td>
<td>1.02</td>
</tr>
<tr>
<td>M2</td>
<td>Massive stone with timber slabs</td>
<td>M4</td>
<td></td>
<td>0.3</td>
<td>0.49</td>
<td>0.616</td>
<td>0.793</td>
<td>0.86</td>
</tr>
<tr>
<td>M3</td>
<td>Brick with concrete slabs</td>
<td>M6</td>
<td></td>
<td>0.3</td>
<td>0.49</td>
<td>0.616</td>
<td>0.79</td>
<td>0.86</td>
</tr>
<tr>
<td>M4</td>
<td>Simple stone with hollow-core slabs</td>
<td>-</td>
<td></td>
<td>0.42</td>
<td>0.61</td>
<td>0.7</td>
<td>0.79</td>
<td>0.9</td>
</tr>
<tr>
<td>M5</td>
<td>Brick with hollow-core slabs</td>
<td>-</td>
<td></td>
<td>0.32</td>
<td>0.5</td>
<td>0.65</td>
<td>0.8</td>
<td>0.87</td>
</tr>
<tr>
<td>M6</td>
<td>Massive stone with hollow-core slabs</td>
<td>-</td>
<td></td>
<td>0.32</td>
<td>0.5</td>
<td>0.65</td>
<td>0.8</td>
<td>0.87</td>
</tr>
<tr>
<td>M7</td>
<td>Brick with timber slabs</td>
<td>M3</td>
<td></td>
<td>0.46</td>
<td>0.65</td>
<td>0.74</td>
<td>0.83</td>
<td>1.02</td>
</tr>
<tr>
<td>REINFORCED CONCRETE (RC)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RC1</td>
<td>Concrete moment frames</td>
<td></td>
<td></td>
<td>0.14</td>
<td>0.207</td>
<td>0.442</td>
<td>0.64</td>
<td>0.86</td>
</tr>
<tr>
<td>RC2</td>
<td>Concrete shear walls</td>
<td>RC5</td>
<td></td>
<td>0.14</td>
<td>0.21</td>
<td>0.386</td>
<td>0.51</td>
<td>0.7</td>
</tr>
<tr>
<td>RC3</td>
<td>Concrete walls and brick masonry walls</td>
<td>-</td>
<td></td>
<td>0.15</td>
<td>0.22</td>
<td>0.4</td>
<td>0.52</td>
<td>0.71</td>
</tr>
<tr>
<td>RC4</td>
<td>Hennebique system</td>
<td>-</td>
<td></td>
<td>0.25</td>
<td>0.3</td>
<td>0.5</td>
<td>0.7</td>
<td>0.85</td>
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<tr>
<td>RC5</td>
<td>Concrete moment frames with infills</td>
<td>-</td>
<td></td>
<td>0.15</td>
<td>0.22</td>
<td>0.402</td>
<td>0.52</td>
<td>0.71</td>
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<tr>
<td>STEEL (S)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>Steel structures (moment and brace F)</td>
<td>S</td>
<td></td>
<td>-0.02</td>
<td>0.17</td>
<td>0.325</td>
<td>0.48</td>
<td>0.7</td>
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<tr>
<td>S2</td>
<td>Old steel structures</td>
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<td>0.15</td>
<td>0.22</td>
<td>0.4</td>
<td>0.52</td>
<td>0.71</td>
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<td>WOOD (W)</td>
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<td></td>
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<td></td>
</tr>
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<td>W1</td>
<td>Timber structures</td>
<td>W</td>
<td></td>
<td>0.14</td>
<td>0.207</td>
<td>0.447</td>
<td>0.64</td>
<td>0.86</td>
</tr>
<tr>
<td>W2</td>
<td>Half-timbered structures</td>
<td>-</td>
<td></td>
<td>0.17</td>
<td>0.24</td>
<td>0.48</td>
<td>0.67</td>
<td>0.89</td>
</tr>
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</table>
Organisation of building stock and vulnerability classes for ISRA calculation tool

Input suitable for ISRA calc. tool, Msc Thesis Delano Landtwing

date of last change: 17.08.2012

1. Storage of settlement information

Storage in structural array for n settlements called building_stock

- Name
- Country
- Classification
- Pop
- Build_tot
- xkoordCH
- ykoordCH
- num_build_age
- num_vuln_perc
- ins_value_bdg
- lmp
- lmp_ECOS09

2. Additional Information on building class distribution

- num_build_vuln
- perc_build

3. Vulnerability index definition for building classes

$mVi$ vulnerability index $V_i$ needs to be defined for each building class

Appendix C: Input Data Format for ISRA calculation tool
Appendix D-1: Output Data Format of ISRA calculation tool

**Abbreviations**

- **BC**: Building Class
- **CD**: Casualty Degree
- **DG**: Damage Grade
- **Mw**: Magnitude
- **PDF**: Probability Density Function
- **VC**: Vulnerability Class

**Intensity (MMI) at different locations**

- **GMPE_fIobs_allLocs_allMags**: 2D-matrix: calculated MMI at all settlements for different Mw

**Mean Damage Grade**

- **fMDG_allVC_allLocs_allMags**: 4D-matrix: MDG for all BC, Mw, VC and settlements

**Damage Grade Distribution**

- **PDF_allVC_allLocs_allMags**: 5D-matrix: percentage of buildings in a damage grade, calculated by PDF

**Number of buildings per Damage Grade**

- **num_build_per_BC_DG**: 5D-matrix: number of buildings per DG and BC, for all VC, settlements and Mw
- **num_build_per_DG**: 4D-matrix: number of buildings per DG (summed over all BC), for all VC, settlements and Mw
Appendix D-2: Output Data Format of ISRA calculation tool

### Insured Value Loss IVL

- **IVL_BC_DG_allVC_allLocs_allMags**  
  5D-matrix:  
  IVL per BC and DG for all VC, settlements and Mw

- **IVL_DG_allVC_allLocs_allMags**  
  4D-matrix:  
  IVL per DG (summed over all BC) and VC for all settlements and Mw

- **IVL_BC_allVC_allLocs_allMags**  
  4D-matrix:  
  IVL per BC (summed over all DG) and VC for all settlements and Mw

- **IVL_tot_allVC_allLocs_allMags**  
  3D-matrix:  
  IVL per settlement and VC for all Mw

### Final Loss Outputs

- **IVL_tot**  
  2D-matrix:  
  IVL summed over all settlements, for all Mw and VC

- **num_DG_final**  
  3D-matrix:  
  number of houses in each DG (summed over all settlements) vs. Mw, for all VC

- **mCasSum_final**  
  4D-matrix:  
  number of casualties (summed over all settlements) for each CD vs. Mw, for all VC

### Hazard Output

- **prob**  
  exceedance probability for all Mw
Appendix E: ISRA calculation tool flow chart

ISRA calculation tool, code architecture
programming was done in Matlab 7.10.0 (R2010a)
last update: 24.08.2012

Model Input

Variable Parameter Input
- Earthquake location
- \(M_{\text{Mmin}}\) for deterministic calculation
- \(M_{\text{Mmax}}\) for hazard calculation

Module selection
- IPE
- EMS Intensity calc.
- for current location

Data Input
- IPE
- saving total loss per magnitude
- for all settlements

IPE
- saving total loss per magnitude
- for all settlements

Mean Damage Grade Calc.
- for all settlements and vuln. classes

Distribution Function
- for all locations/settlements

Cost Estimation
- (IVL)
- Number of houses per Damage Grade

Casualty Estimation
- loop over all locations/settlements
- loop over all magnitudes
- from \(M_{\text{Mmin}}\) to \(M_{\text{Mmax}}\)
- loop over all vulnerability classes (V-, V0, V+)
- loop over all building classes (M1, M2, etc.)
- Distance Calc.
- distance b/w earthquake and location/settlement

Additional Parameter Input
- Time-window

Deterministic Calculation

Input for Hazard Calculation

Deterministic Calculation Input
- distance earthquake-settlement

Hazard Calculation

- Distance Calculation
- \(d(iLoc,1)\) for location/settlement

- casualty index
- casualty rates
- forecast rates for hazard calculation

Input format:
- building stock:
  - cell array for locations (1 x #loc.)
  - see also Appendix C
- building classes:
  - matrix building classes x vuln. index
  - Vi
  - BC
  - VC (V-, V0, V+)

Input format:
- location in Swiss Coordinates:
  - building_stock{iloc}.xkoordCH
  - building_stock{iloc}.ykoordCH

Output format:
- GMPE_dist_epi/hyp(iLoc,1)
- distance
- [km]

Output format:
- GMPE_fIobs(iLoc,1)
- observed intensity
- [EMS-98]

Selection is done automatically
- fct_GMPE_Allen2012
- fct_GMPE_ECOS_02
- fct_GMPE_ECOS_02_new
- fct_GMPE_ECOS_09

Selection needs to be done manually
- fct_mean_damage_degree.m (used in SERIANEX)
- fct_mean_damage_degree_calib_Allen.m (calibrated for Allen-2012)
- fct_mean_damage_degree_calib_ECOS09.m (calibrated for ECOS-09)

Selection is done automatically
- fct_damage_grade_distribution_bin.m (Binomial PDF)
- mxyPDF

Input format:
- mean damage grade (\(f_{\text{MDG}}\))

Output format:
- mean damage grade (\(f_{\text{MDG}}\))

input format:
- GMPE_fIobs_allLocs_allMags
- \(M_i\)

output format:
- mean damage grade (\(f_{\text{MDG}}\))

\(f_{\text{MDG}}\) allVC_allLocs_allMags
- PDF_allVC_allLocs_allMags
- IVL_BC_DG_allVC_allLocs_allMags
- IVL_BC_allVC_allLocs_allMags
- IVL_DG_allVC_allLocs_allMags
- IVL_tot_allLocs_Mags

\(\text{num build per BC}_\text{DG}, \text{num build per DG}\)
- cost estimation (IVL)
- \(I_{\text{VU}}_{\text{tot}}\)

\(f_{\text{MDG}}\) allVC_allLocs_allMags
- PDF_allVC_allLocs_allMags

input format:
- GMPE_fIobs_allLocs_allMags
- mV

output format:
- mean damage grade (\(f_{\text{MDG}}\))

input format:
- GMPE_fIobs_allLocs_allMags
- \(M_{\text{min}}\)

output format:
- mean damage grade (\(f_{\text{MDG}}\))

input format:
- GMPE_fIobs_allLocs_allMags
- M_{\text{min}}

output format:
- mean damage grade (\(f_{\text{MDG}}\))

Selection is done automatically
- fct_damage_grade_distribution_bin.m (Binomial PDF)
- mxyPDF

Selection is done automatically
- fct_damage_grade_distribution_bin.m (Binomial PDF)
- mxyPDF

Appendix E: ISRA calculation tool flow chart

Legend
- calculation modules
- internal input/output formats
- secondary scripts (functions)
- final output storage
(see also Appendix C)
- Loops