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Decision Making under Uncertainty
Developing the Seismic Design Basis for Critical Infrastructures

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Decision Making under Uncertainty – Developing the Seismic Design Basis for Critical Infrastructures

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Disclaimer:

The views and opinions of the author expressed in the paper do not necessarily state or reflect those of the Nuclear Power Plant Goesgen and shall not be misrepresented as such.

Contents of the Presentation

- Introduction
- Procedure for the development of the seismic design basis of critical infrastructures
- Practical application- design of a fictive new nuclear power plant
- Seismic risk evaluation (PSA)
  - – Comparison with PSHA results

Introduction

- Planning of critical infrastructures is associated with large project risk for investors
  - Large involvement of political and other societal stakeholders
    - “Zero risk” environment in wealthy countries
  - Long investment times (large amortization periods)
- Seismic design can be an important risk contributor
  - Large effort to develop the seismic design basis
  - Later changes of the design basis can jeopardize the investment

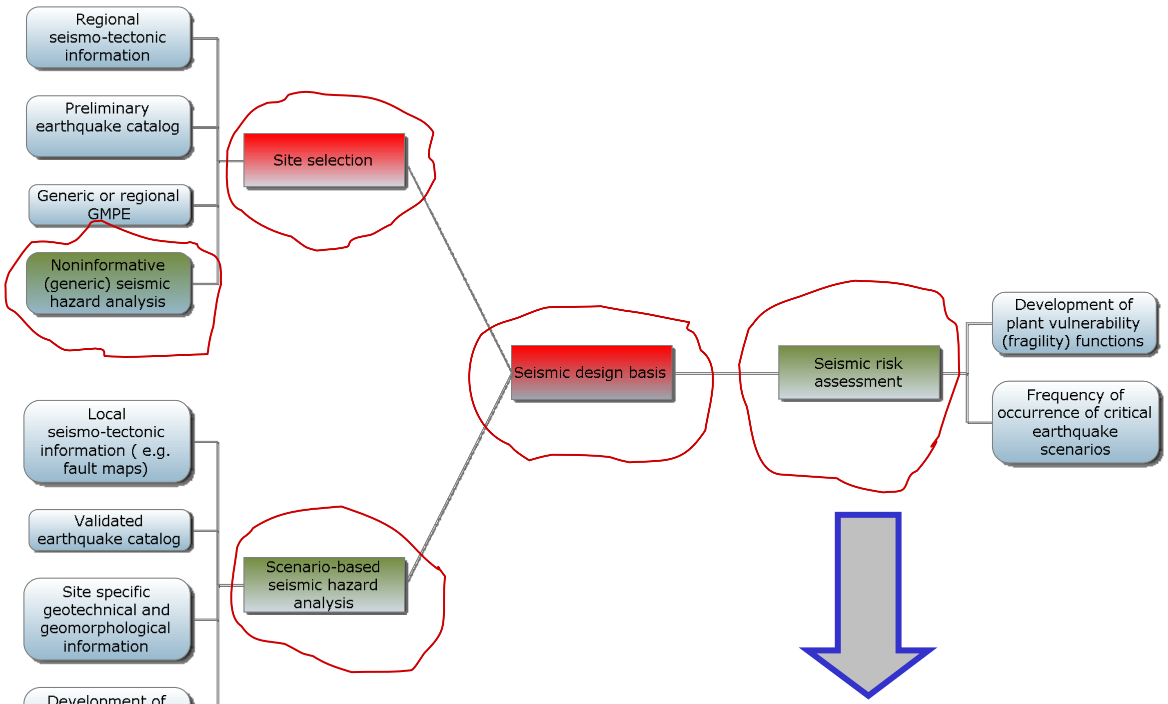
Introduction

- Nuclear installations (NPPs) represent typical examples for critical infrastructures
  - Special challenges in Europe : planning/construction/commissioning may last for 15 to 20 years
  - Project risks are not covered by governmental guarantees as in the U.S.A
  - Seismic design procedures as f. e. in the U.S.A (NRC RG 1.165 or 1.208) are very cumbersome and may not lead to robust results
  - Need for a more robust procedure

Introduction

- Key requirements to such a procedure
  - – Commensurate to the decision making process
  - – Time-invariant results (related to the lifetime of the infrastructure)
    - Safety margins but still competitive in a global market
    - Easy to develop and to implement,
    - Later refinements shall not lead to drastic (cliff-edge) changes of the design basis
  - – Commensurate to the degree of information available for the analysis

Procedure for the development of the seismic design basis



Regional seismo-tectonic information

Preliminary earthquake catalog

Generic or regional GMPE

Noninformative (generic) seismic hazard analysis

Local seismo-tectonic information (e.g. fault maps)

Validated earthquake catalog

Site specific geotechnical and geomorphological information

Development of controlling earthquake scenarios

Site selection

Scenario-based seismic hazard analysis

Seismic design basis

Seismic risk assessment

Development of plant vulnerability (fragility) functions

Frequency of occurrence of critical earthquake scenarios

Assessment of seismic margins

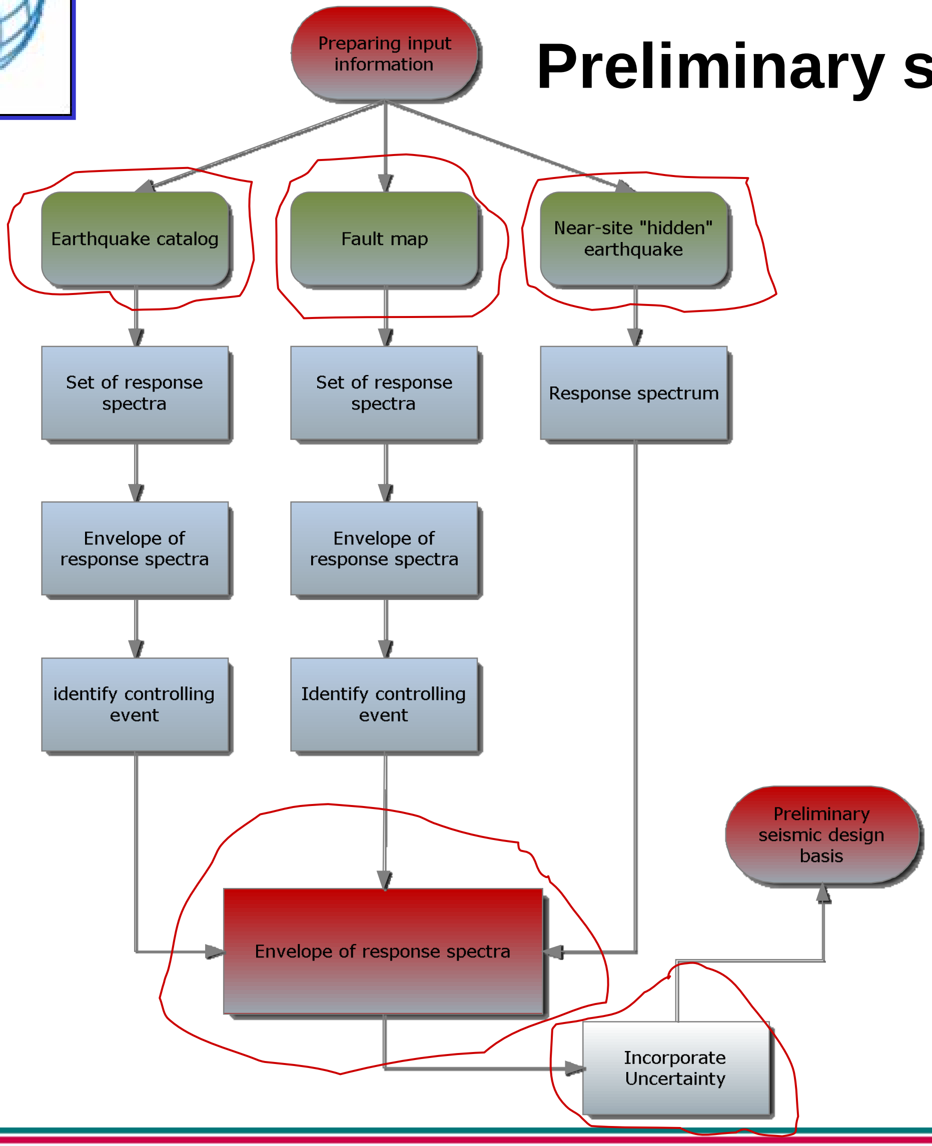
Major steps

(1) Generic non-informative SHA

(2) Scenario-based informative SHA

(3) Seismic Risk Analysis

Procedure – Preliminary seismic design basis, site selection



Basic concept:

(1) Identify all possible sources of seismic activity

(2) Develope an enveloping response spectrum

(3) Identify controlling events

(4) Incorporate "Uncertainty"

Procedure – Preliminary Seismic Design Basis (PrSD)

- The development of the preliminary seismic design basis is based
  - On generic/regional seismo-tectonic information
  - Generic Ground Motion Prediction Equations (GMPEs)
  - Preliminary site information
- Requires the definition of “target parameters” for engineering evaluations (e.g. response spectra + strong motion duration)
- Note: For site selection the process may have to be performed for several sites

Procedure – Preliminary Seismic Design Basis (PrSD)

- Important remark
  - Consideration of “near site seismic source”
    - Either based on available fault maps, or
    - “Non-informative judgment” based on the resolution limits of the preliminary site information program
    - Suggestion – Minimum: M_w=5.5, distance half of the expected fault rupture length or corresponding fault length;
  - Many NPPs of today do not meet this requirement

Procedure – Preliminary Seismic Design Basis (PrSD)

- Incorporation of Uncertainty
  - For the enveloping response spectrum:

$$S_a(f) = S_a(f)_{env} * \exp\left(\sigma_{total}^2 / 2\right)$$

$$\sigma_{total} = \sqrt{\left(\sigma_{epi}^2\right) + \left(\sigma_{aleatory}^2\right)}$$

Safety factor of 1.3-1.4

- For the strong motion duration:

▪ Take the largest strong motion duration of any of the underlying controlling events

Scenario-Based SHA, Refinement of Seismic Design Basis

- Confirmation or adjustment of design basis by application of waveform modeling
- Check/approve the controlling earthquake events from the previous analysis
  - Applying results from more detailed site investigations
  - Refined (local) fault map
  - Refined earthquake catalogue
- Develop source and site specific model

Scenario-Based SHA, Refinement of Seismic Design Basis

- Quantify the resulting response spectra and strong motion duration for the controlling events
  - Sensitivity/Uncertainty analysis on critical model parameters or
  - stochastic waveform model
- Approve or adjust the design basis
  - The expected (or most likely) hazard should fall below the preliminary seismic design basis for approval
  - The strong motion duration shall fall below the previously estimated strong motion duration or
  - Use damage-scaled response spectra for comparison

Damage-scaled response spectra

In a first order of approximation damage (significant deviation from linear behavior) for identical spectral shapes scales with the square root of the strong motion duration

$$S_a\left(f\right)_{scaled} = S_a\left(f\right)_{ContEvent} * \frac{\sqrt{t_{SM,ContEvent}}}{\sqrt{t_{SM,\Pr SD}}}$$

The Preliminary Seismic Design Basis (PrSD) is still acceptable if the damage-scaled response spectrum of the most critical controlling event is lower (with some margin) than the PrSD

Seismic Risk Analysis

- Purpose:
  - – Quantification of safety margins considering uncertainties
- Requires a probabilistic description of seismic hazard and
- a vulnerability (fragility) function of the critical infrastructure for the “target evaluation function”
    - NPPs – core damage; other: capital loss function
- Important: “Seismic Risk” cannot be evaluated based on a probabilistic seismic hazard description alone

Methodology of risk analysis

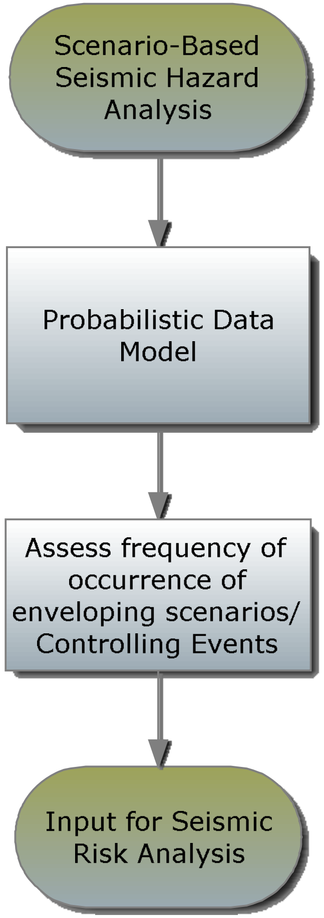
1. Identification of events that can occur and have adverse consequences
2. Estimation of the likelihood of those events occurring
3. Estimation of the potential consequences.

Results can be represented as a set of triplets characterizing different risk scenarios

$$R = \langle H_i, P_i, C_i \rangle$$

H_i-events;P_i- probability;C_i-consequences

Probabilistic Description of Seismic Hazard



Scenario-Based Seismic Hazard Analysis

Probabilistic Data Model

Assess frequency of occurrence of enveloping scenarios/ Controlling Events

Input for Seismic Risk Analysis

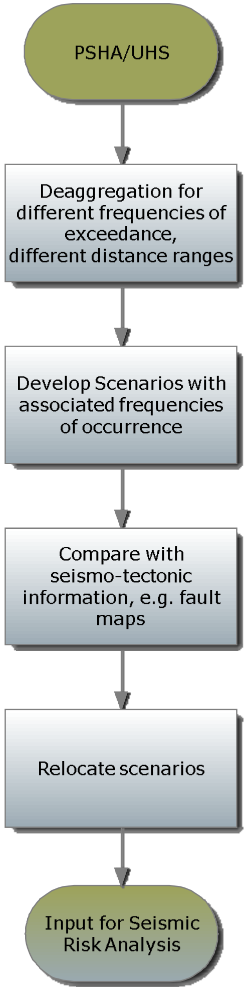
Direct Scenario-based approach,

Klügel et al (2006)

Advantage:

- **Direct use of seismo-tectonic information**
- **the most suitable data model can be applied,**
- **time-dependent models can be used**

Probabilistic Description of Seismic Hazard


PSHA/UHS

Deaggregation for different frequencies of exceedance, different distance ranges

Develop Scenarios with associated frequencies of occurrence

Compare with seismo-tectonic information, e.g. fault maps

Relocate scenarios

Input for Seismic Risk Analysis

Use of traditional PSHA;

Requires deaggregation of UHS and development of scenarios;

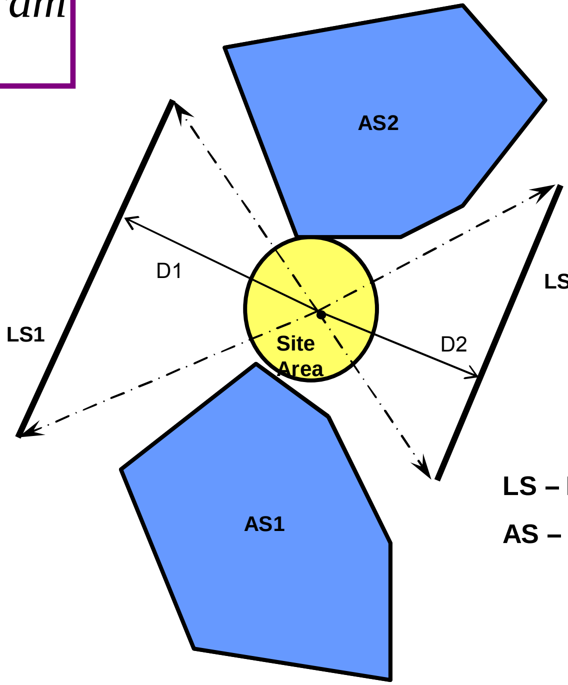
Sometimes called hybrid approach

UHS do not allow to make meaningful assessments on the damaging impact of causative earthquakes

Mathematical model of traditional PSHA

$$E(a)=\sum_{i=1}^{N}\nu_i\int_{m_0}^{m_u}\int_{r=0}^{\infty} f_i(m)f_i(r|m)P(S_a>a|m,r)\,drdm$$

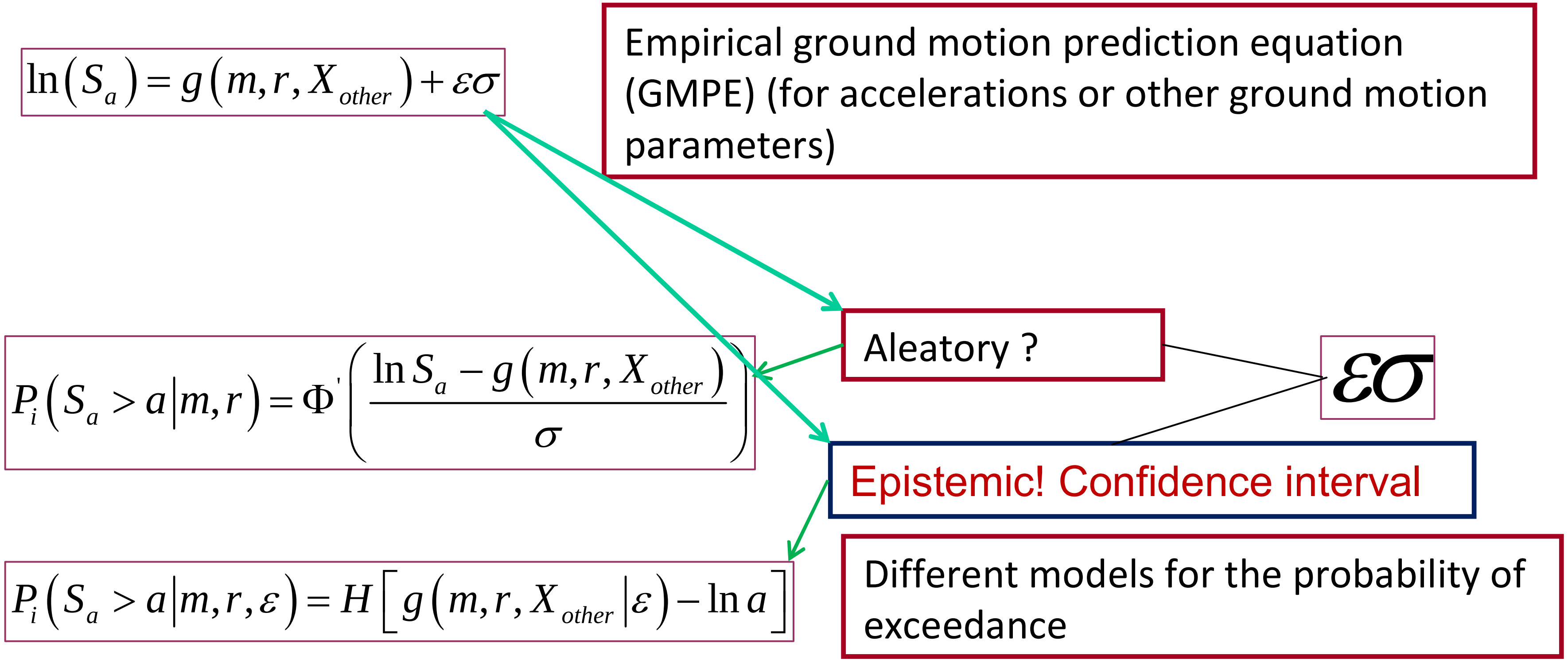
$E(a)$	Mean exceedance frequency of ground motion level a (or Intensity)
ν_i	Mean rate of occurrence of earthquakes within integration bounds
$P_i(S_a>a\|m,r)$	Probability of exceedance
$f_i(m)$	pdf oft the magnitude-frequency relationship
$f_i(r\|m)$	pdf of distance between earthquake location and site



LS – Line Source

AS – Areal Source

Mathematical Model of traditional PSHA



$$\ln(S_a) = g(m, r, X_{other}) + \varepsilon\sigma$$

Empirical ground motion prediction equation (GMPE) (for accelerations or other ground motion parameters)

Aleatory ?

$\varepsilon\sigma$

$$P_i(S_a > a | m, r) = \Phi'\left(\frac{\ln S_a - g(m, r, X_{other})}{\sigma}\right)$$

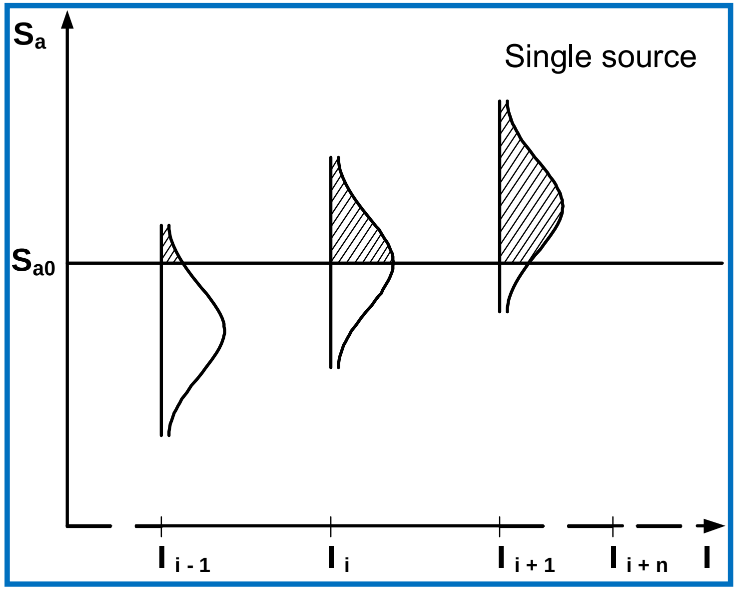
Epistemic! Confidence interval

$$P_i(S_a > a | m, r, \varepsilon) = H\left[g(m, r, X_{other} | \varepsilon) - \ln a\right]$$

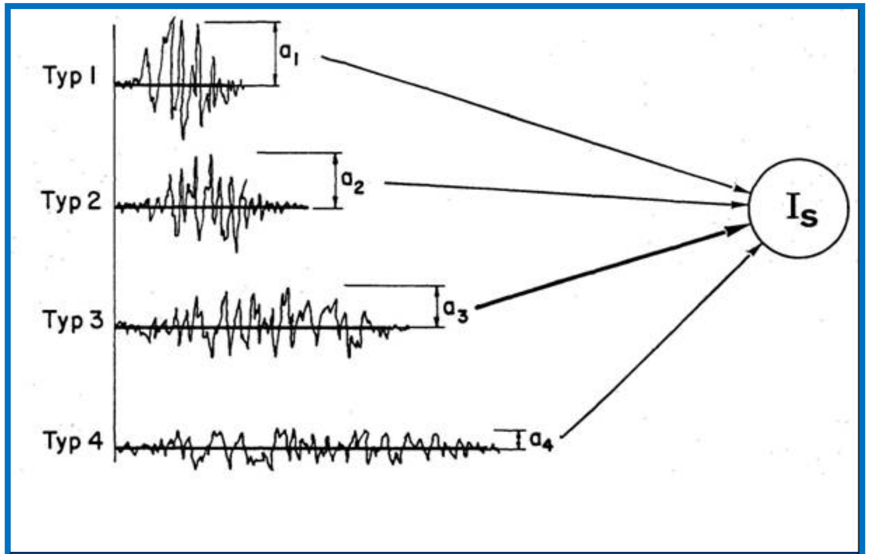
Different models for the probability of exceedance

Results strongly differ!

Impact of the traditional PSHA model



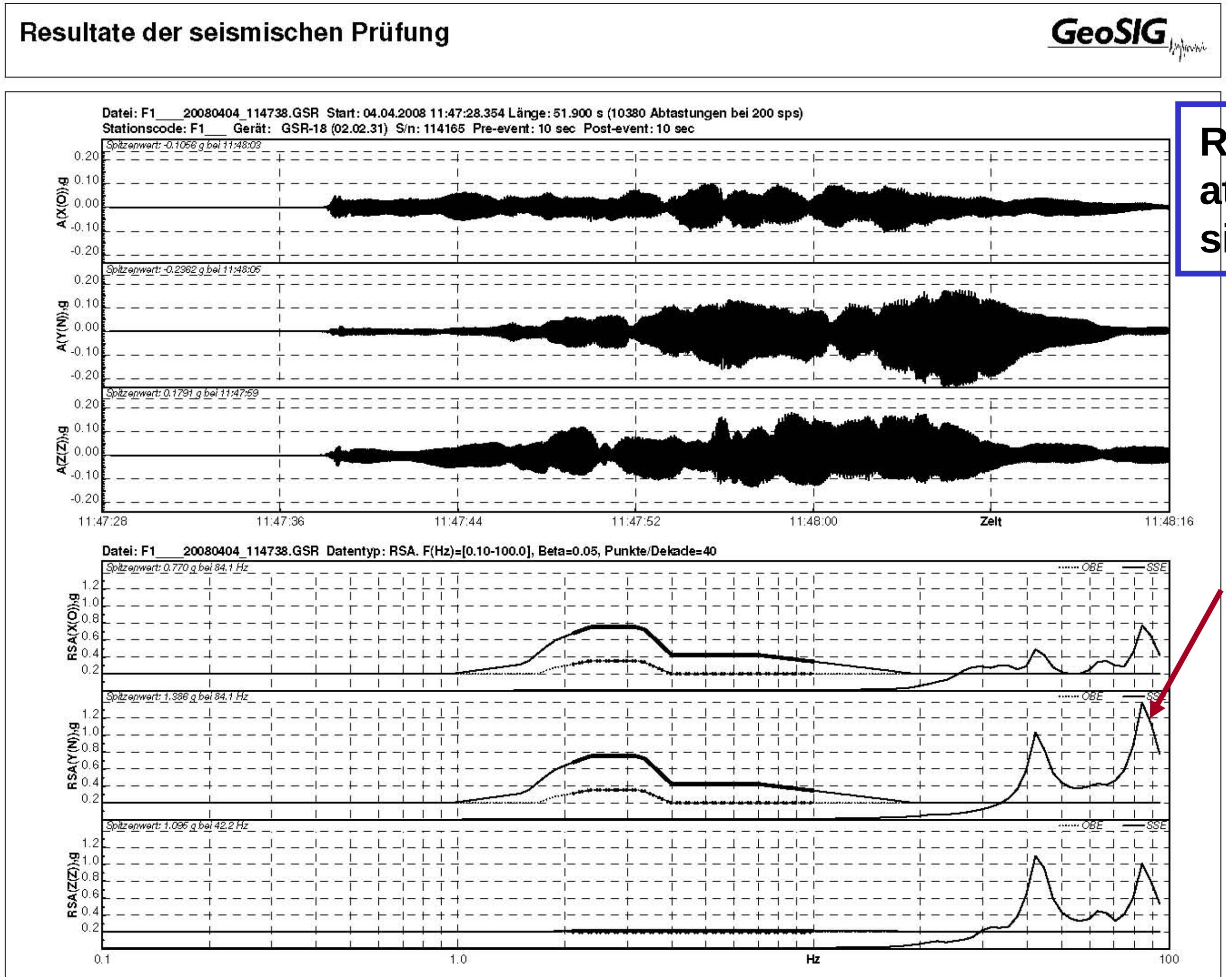
PSHA adds weighted contributions of earthquakes for the UHS with completely different damaging effects



Different time histories with different pga values lead to the sime site intensity

On the basis of an UHS it is not possible to make any meaningful judgement on the damaging effects of earthquakes or on seismic risk

Are local accelerations a damage indicator?



Resultate der seismischen Prüfung

GeoSIG

Datei: F1____20080404_114738.GSR Start: 04.04.2008 11:47:28.354 Länge: 51.900 s (10380 Abtastungen bei 200 sps)
Stationscode: F1___ Gerät: GSR-18 (02.02.31) S/n: 114165 Pre-event: 10 sec Post-event: 10 sec

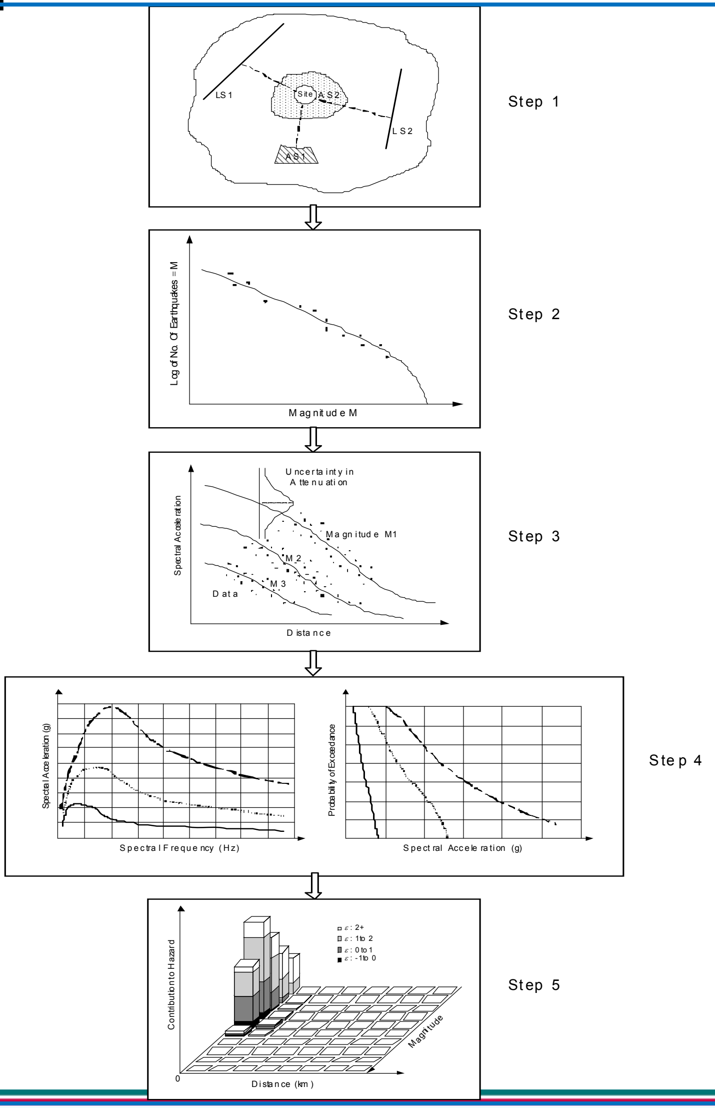
Datei: F1____20080404_114738.GSR Datentyp: RSA. F(Hz)=[0.10-100.0], Beta=0.05, Punkte/Dekade=40

Recording at Goesgen site

1.33g

New developments, scenario-based (hybrid) approach

- UHS (uniform hazard spectra) not used for seismic PSA;
- Deaggregation of UHS into scenario earthquakes;
- Scenarios can be characterized by their physical properties and their damaging consequences can be defined adequately
  - recorded or simulated time-histories
- Possible to consider
  - focal mechanisms
  - Directivity or topographical effects
- Important for realistic risk assesment like a PSA (PSA is based on limit state analysis)

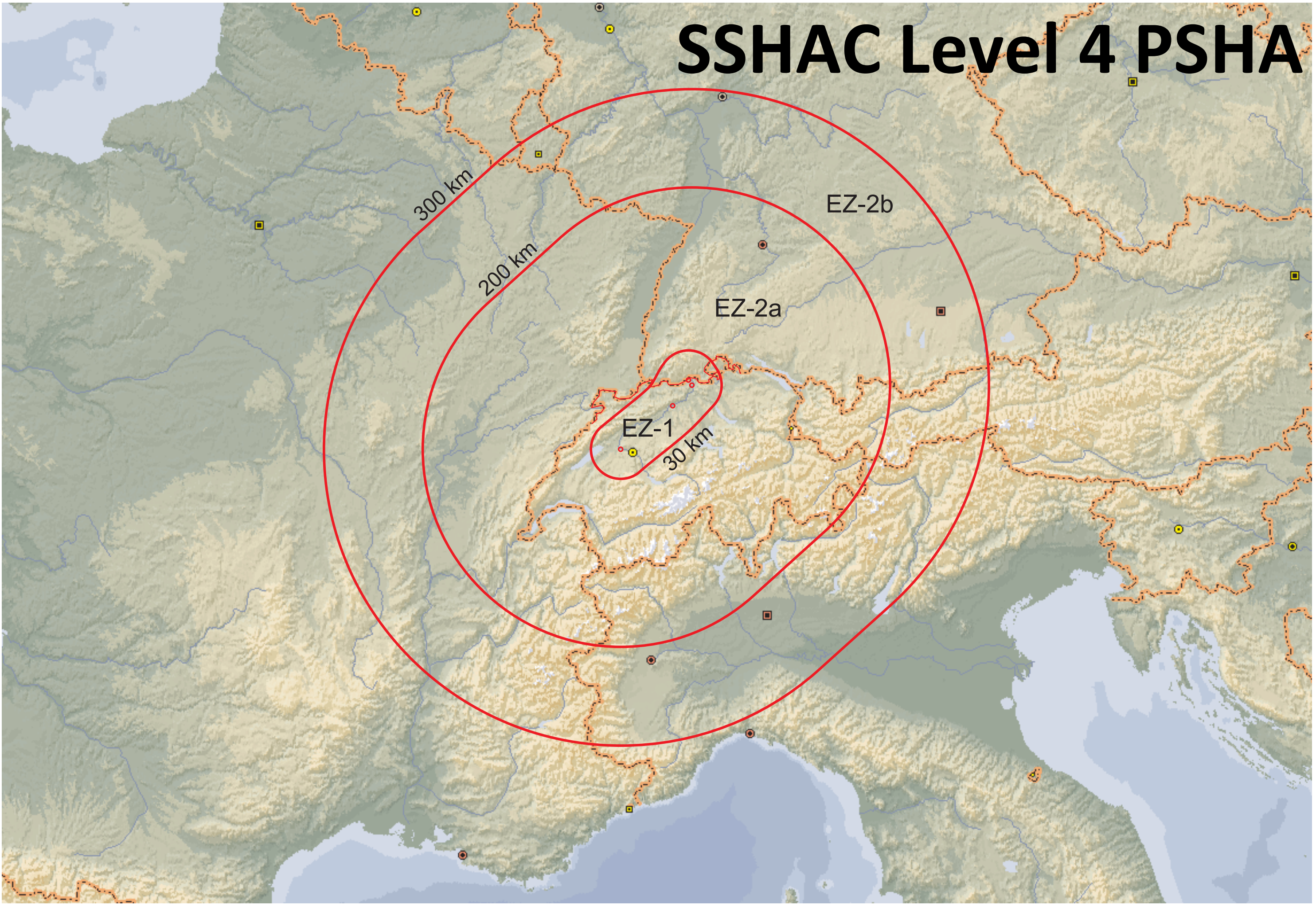


Application of the procedure

- Case study: Construction of a new nuclear power plant at the site of the existing nuclear power plant Goesgen
- Advantage: several seismic hazard studies have been performed in the past; a large amount of investigation results is readily available, including the results of the PEGASOS project (SSHAC Level 4 PSHA, completed in 2004);
- Detailed geological information collected by NAGRA as part of the search for a final repository for radioactive waste

PEGASOS – Project 2000-2004

SSHAC Level 4 PSHA



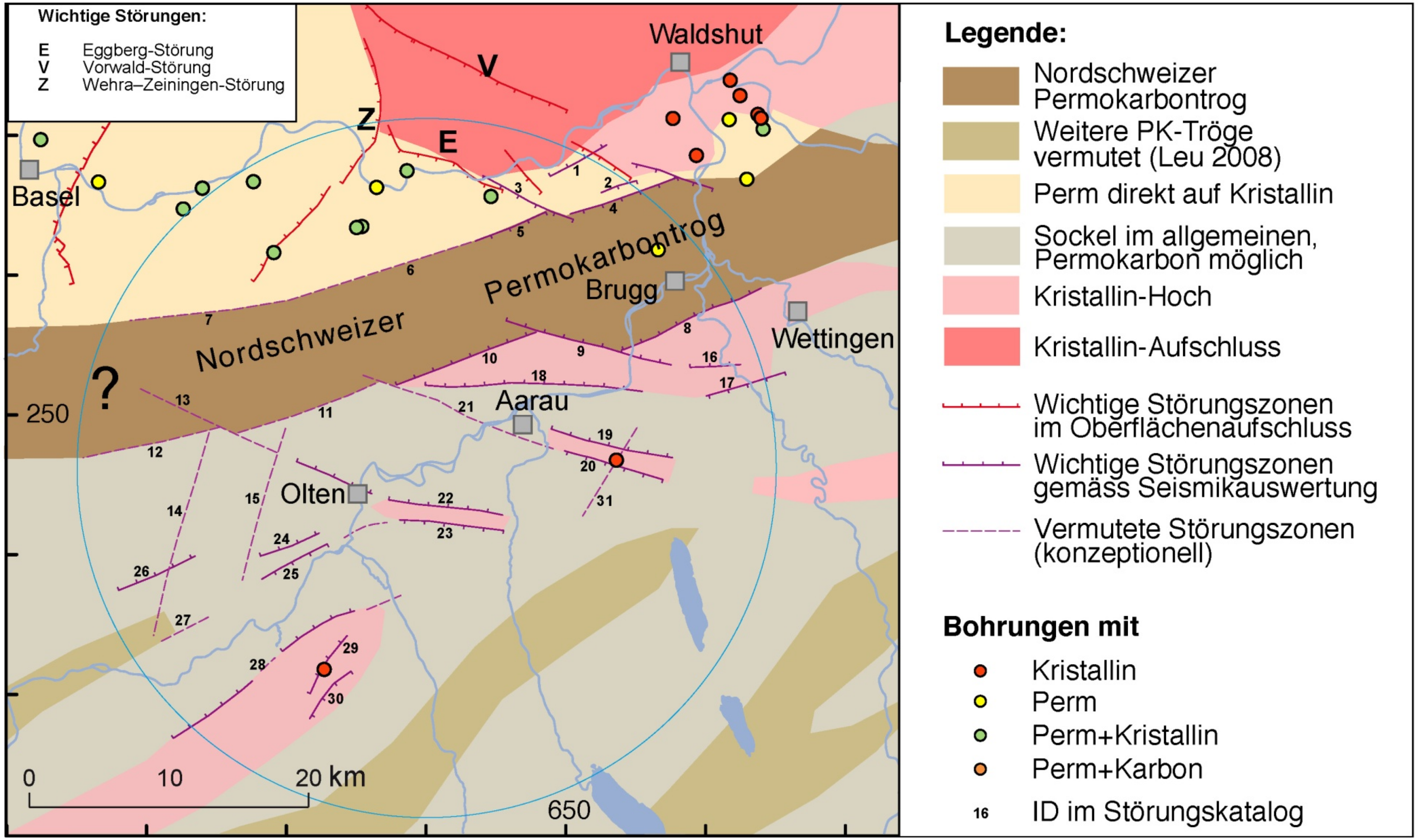
Preliminary seismic design basis, sources of information

- Historical and recorded earthquakes:
  - Earthquake catalogue of Gösgen (site-specific collection) based on ECOS2002 (SED) and a comparison with catalogues of neighbor countries (Grünthal& Wahlström, 2003, BGR (Leydecker)),
  - New information on Basel (1356) earthquake
- Seismo-tectonic information, fault maps
  - Swisstopo map (2005) - regional
  - NAGRA (2008) – local information
- Near-site hidden earthquake
  - NAGRA (2008) is sufficiently detailed

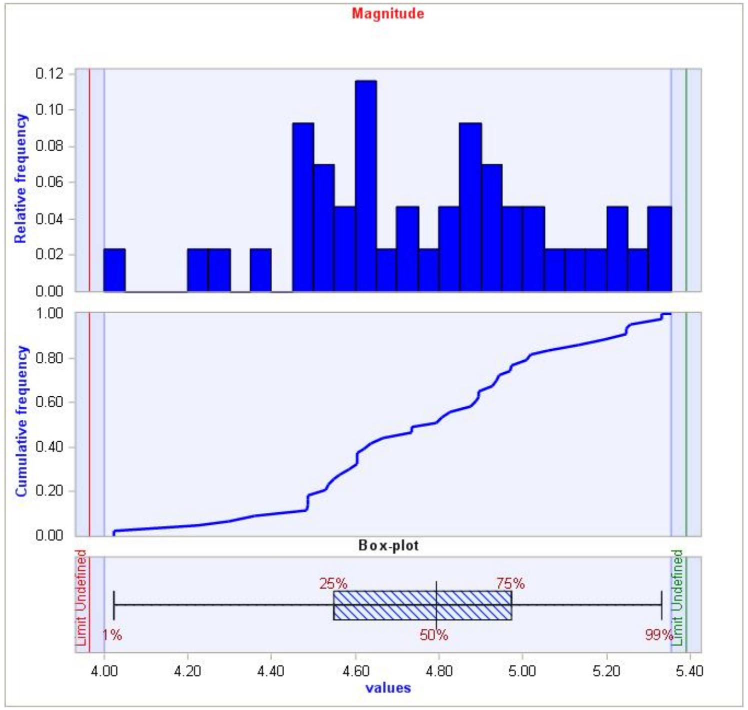
Earthquakes with magnitude larger 5 within 100 km distance of the Goesgen site

YEAR	LOCATION	MW_CATALOG, GOESGEN	DISTANCE, KM
250	Kaiseraugst (Augusta Raurica)	6	25.05
1721	Aesch	5	30.01
1356	Basel	6.6	30.01
1356	Basel	5.4	34.42
1650	Basel	5.3	38.79
1777	Sarnen	5.1	57.87
1601	Unterwalden	5.9	57.89
1964	Sarnen	5.3	61.55
1774	Altdorf	5.7	78.40
1729	Frutigen	5.2	85.78

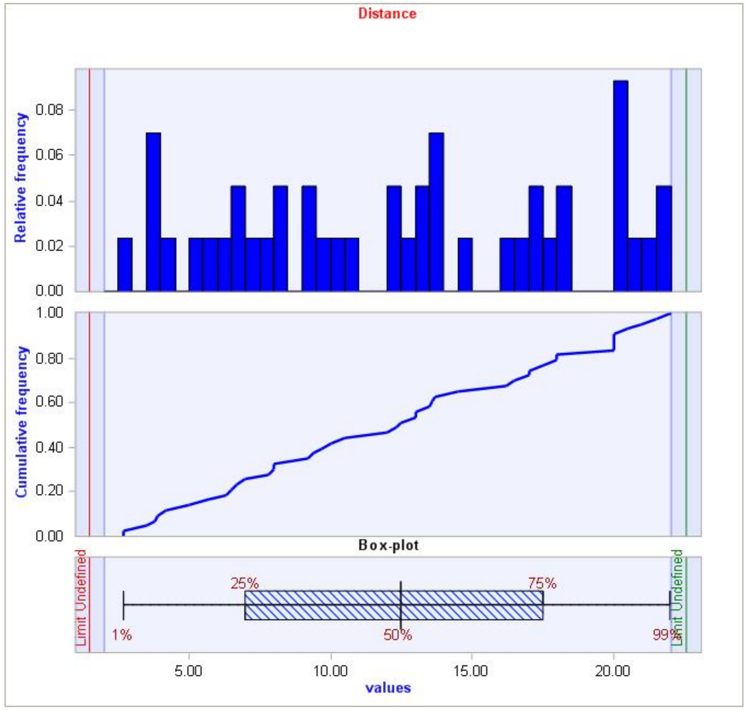
Fault and distortion map, macroseismic scale (NAGRA)



Magnitude and Distance distribution, local fault map



Magnitude distribution, mean Mw=4.8



Shortest distance distribution, mean d=12.4km

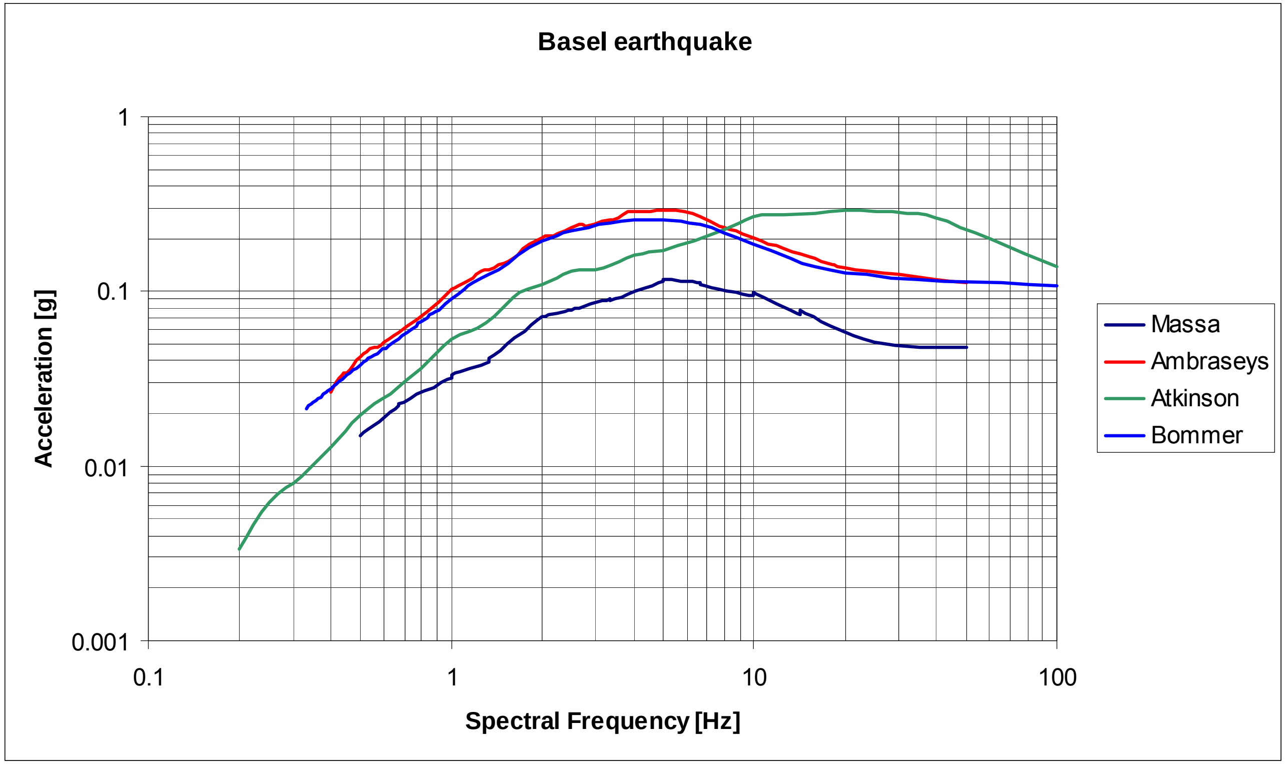
Preliminary Seismic Design Basis, GMPE

- Equations of Ambraseys et al (2005) were selected;
  - For the larger horizontal component
  - Swiss co-author (P. Smit), who developed the first GMPE for PGA in Switzerland including Goesgen data (1995)
  - Attempt to check the invariance of error (sigma) under nonlinear transformation
  - Found to be conservative by comparison with other European GMPEs

$$\log y = a_1 + a_2 M_\mathrm{w} + (a_3 + a_4 M_\mathrm{w}) \log \sqrt{d^2 + a_5^2} \\ + a_6 S_S + a_7 S_A + a_8 F_N + a_9 F_T + a_{10} F_O,$$

Equation applied for Stiff soil

Comparison of GMPEs, stiff soil conditions



Massa et al– North Italy, (2008);

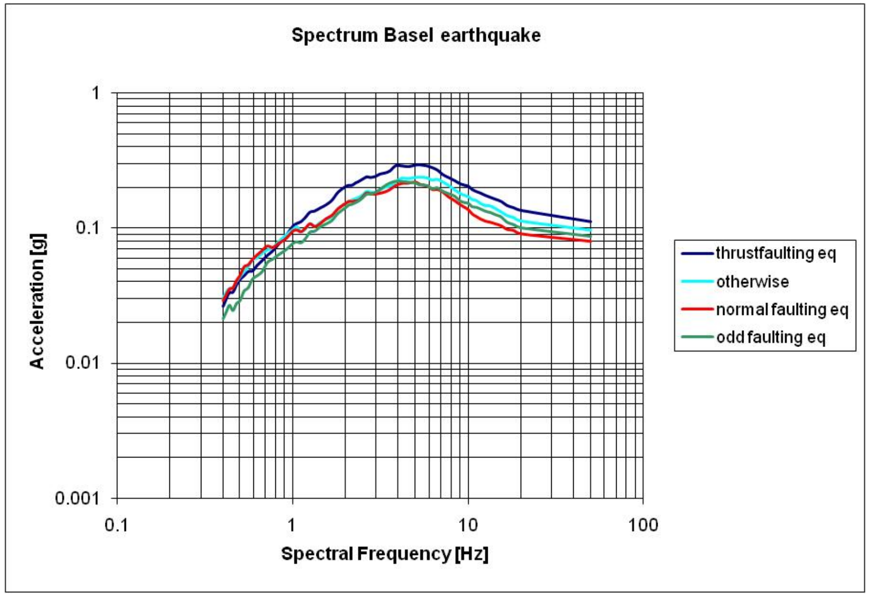
Ambraseys et al, Europe/Asia Minor (2005);

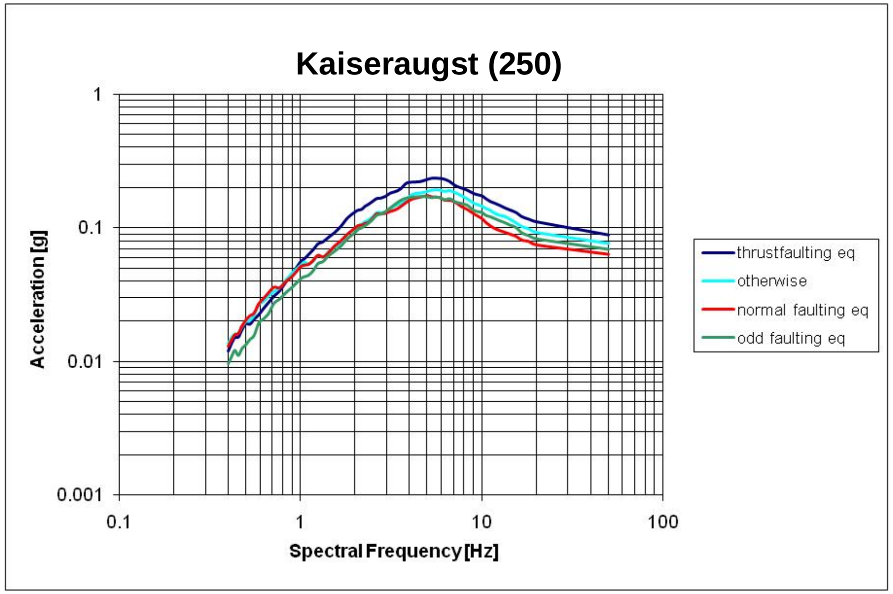
Atkinson & Boore (CEUS), 2006

Akkar & Bommer (2010) – geometric mean! (same database as Ambraseys!?)

Geometric mean according to Akkar & Bommer 2010 is lower than the larger horizontal component according to Ambraseys et al (2005) – same database

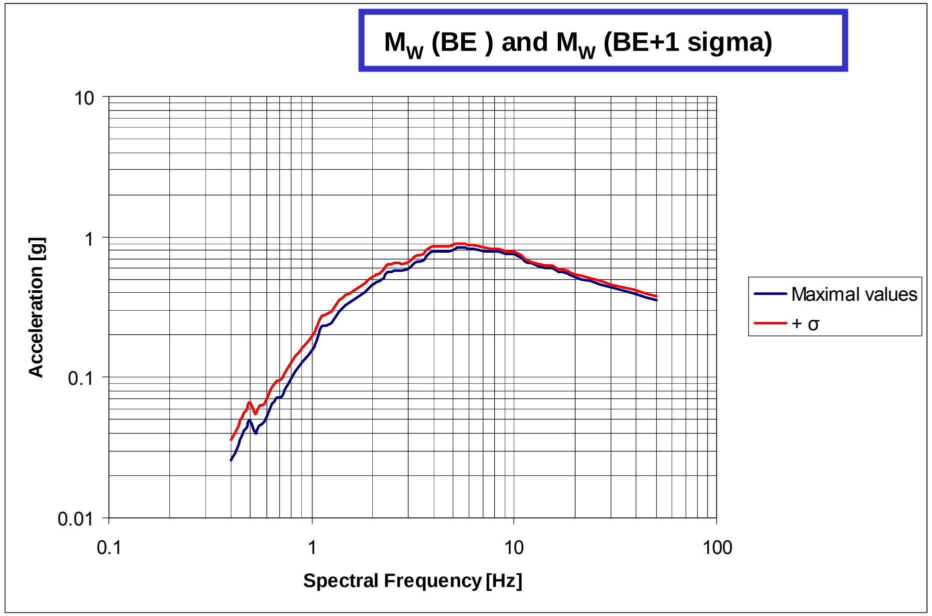
Preliminary Seismic Design Basis – Controlling Historical Event

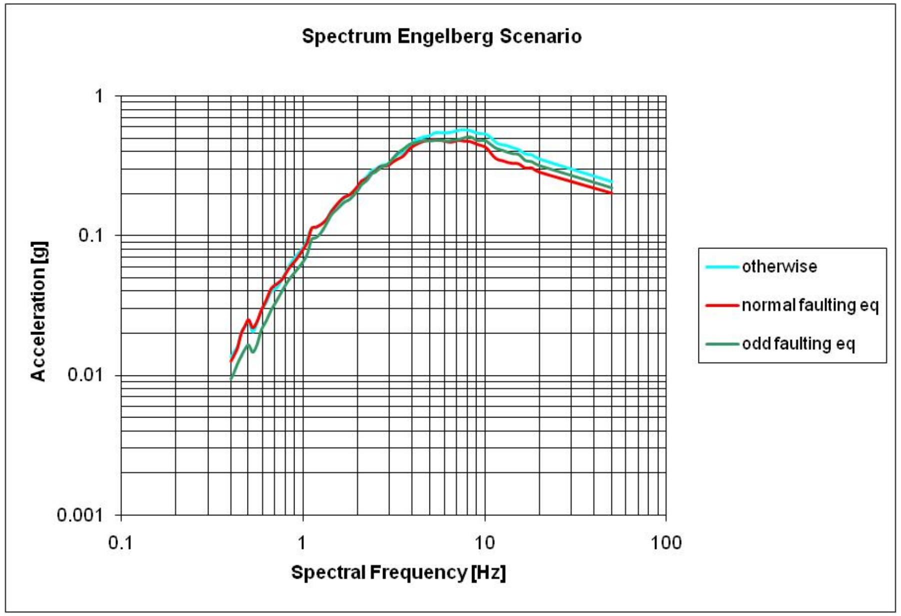




The controlling historical event is the Basel earthquake (Mw=6.6,1356), PGA=0.112g on surface, this event envelopes all other recorded earthquakes

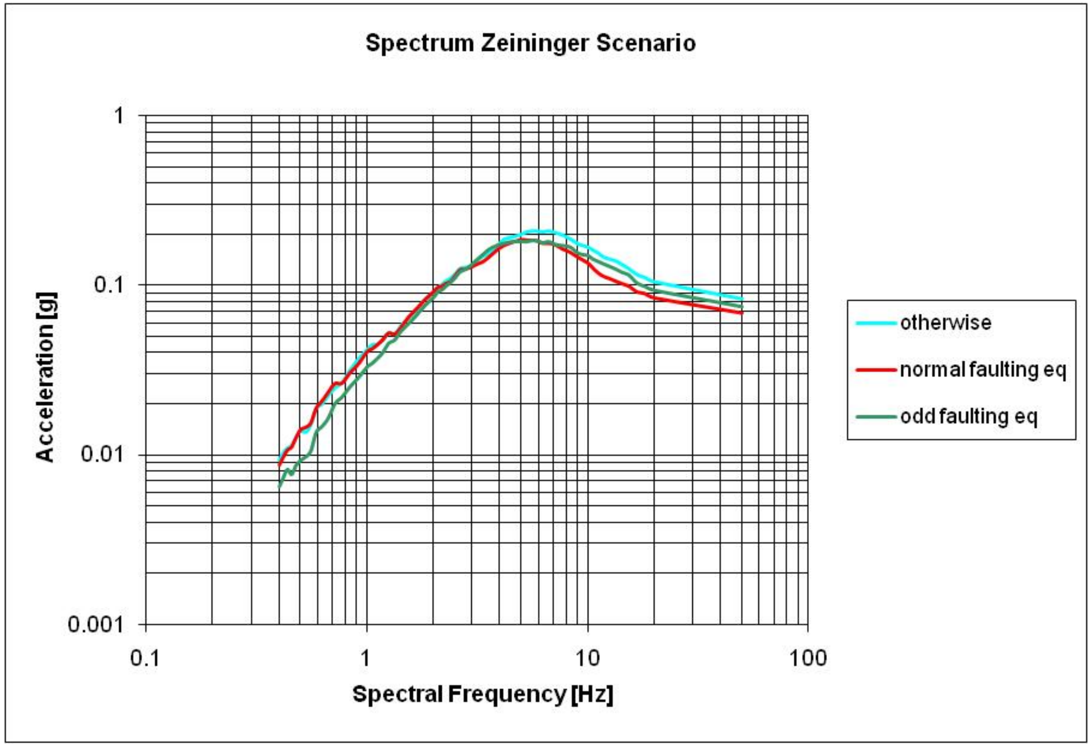
Preliminary Seismic Design Basis – Controlling event from local fault map





Assumption: All mapped faults are active or can be reactivated during the lifetime of the new NPP, controlling event Engelberg scenario (Mw=5.2, 4.2km)

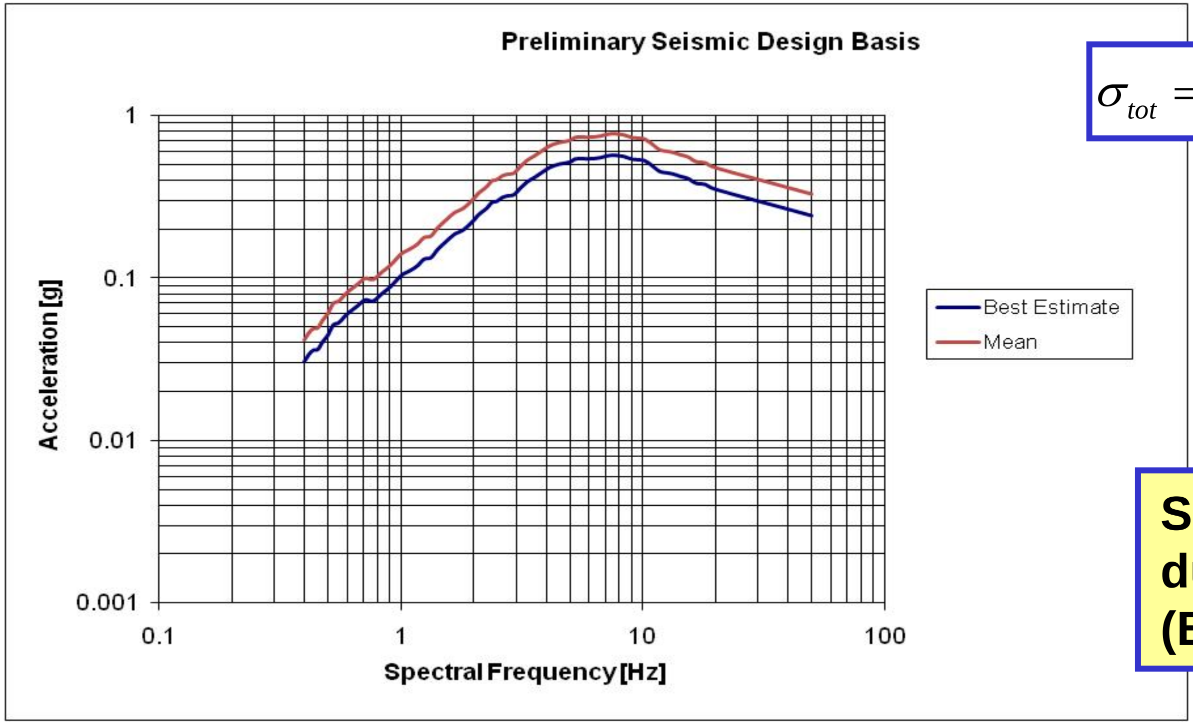
Controlling event from regional fault map



Controlling event Zeininger scenario, Mw=5.6, d=18.9km;

Does not effect the design basis

Incorporation of Uncertainty -Final Preliminary Seismic Design Basis (PrSD)



$$\sigma_{tot} = \sqrt{\sigma_{epi}^2 + \sigma_{aleat}^2} \approx 0.78$$

F=1.36

Strong Motion duration T_{RMS} ~14 s (Basel scenario)

PrSD spectrum is anchored at PGA=0.33g (larger horizontal component)

Scenario-based SHA- refinement (approval) of seismic design

- Waveform modeling techniques are used to confirm the selected design basis
- In the case study – a stochastic simulation technique is applied
  - Idea - empirically observed earthquake time histories are treated as a sample from a “feasible” population of time histories;
  - The population of time histories is defined by the source characteristics; instationarity of source characteristics is random;

Modeling parameters of the Goesgen stochastic source model

Parameter	**Value, Model**
Source spectrum	Brune -square, with equivalent circular source dimensions, source radius *a* magnitude dependent,
Stress drop	Not required, explicit magnitude scaling;
Geometric attenuation	Set of piecewise functions, near fault D<a, $1/(SRL+1)^2$ D<70km, 1/D D>70km, $1/D^{-0.71}$, near fault constraint $4/a^2$ with a>=1;
Path attenuation	$270 f^{0.5}$
Shear velocity, [km/s] β_S	3.5
Density, [kg/m^3]	2800
Site attenuation	$\kappa = 0.006 + 0.25\exp\left(-0.8\left(D - SRL\right)\right)$ $SRL = -3.22 + 0.69 \cdot \max\left(M_w, 4.7\right)$
Site amplification	Boore et al,(1997) $\left(\beta_S / V_{s,30}\right)^{BV(f)}$

Near Field term

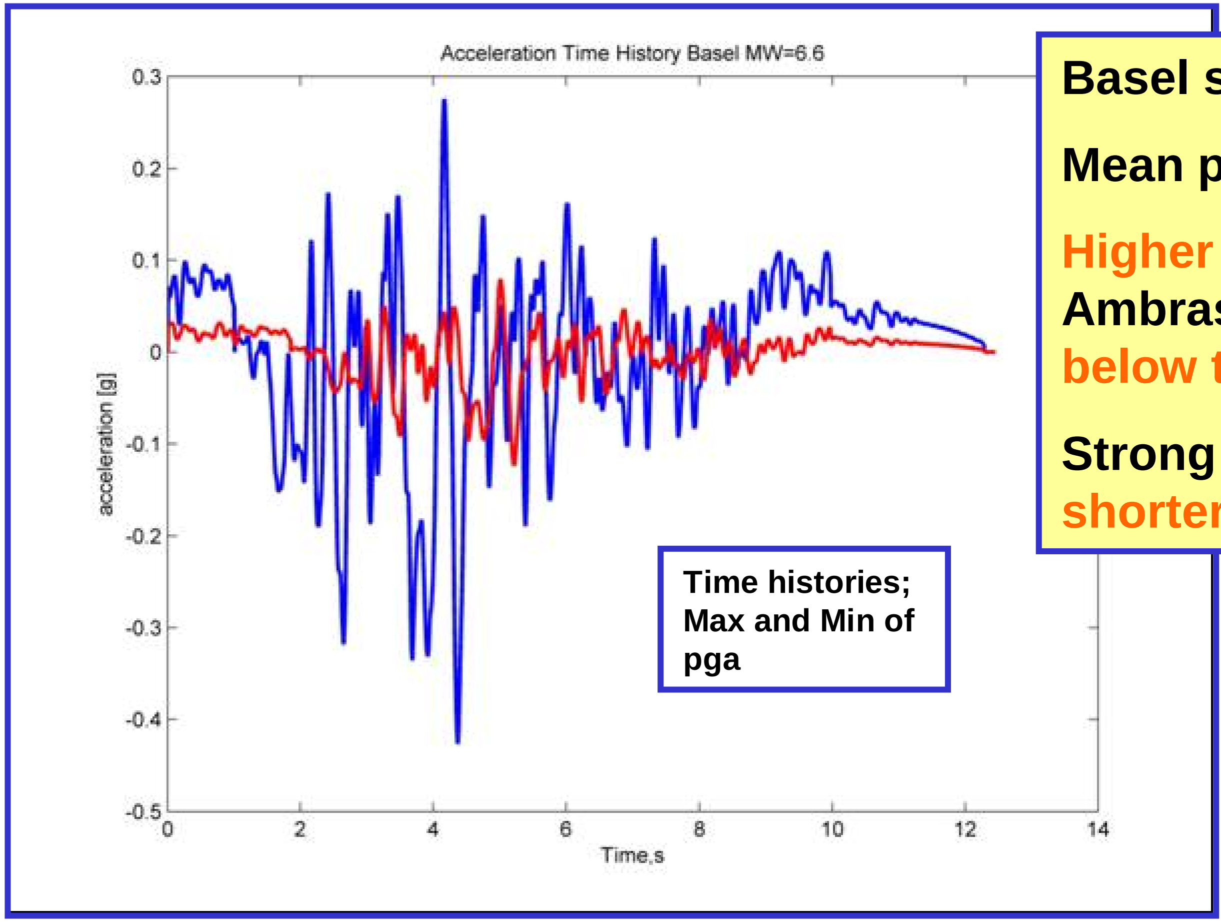
Comparison with recorded data

Earthquakes are very rare events in Switzerland, 3 records registered at the Goesgen site

Date	Earth-quake location	Distance to Goesgen site, [km]	Magnitude, M_w	PGA measured, x-direction, [mg]	PGA, measured y-direction, [mg]	PGA, geometrical mean, [mg]	Com-puted mean PGA, [mg]
12.11.2005	Mönthal (Frick)	27.93	3.6	13.51	15.76	16.85	16.7
05.12.2004	Waldkirch	80.01	4.6	11.63	15.31	17.17	14.9
21.06.2004	Liestal	31.98	3.4	7.72	9.76	11.24	10.9

The mean was calculated from a set of 100 simulated time histories

Analysis for controlling events



Time histories; Max and Min of pga

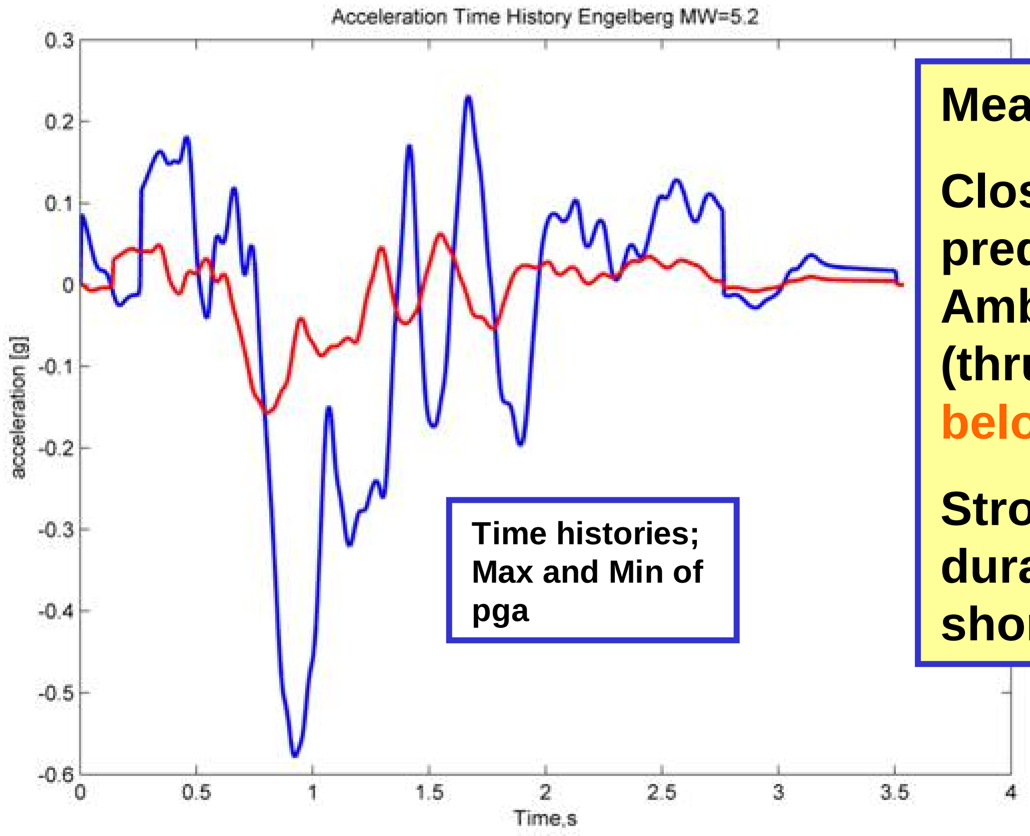
Basel scenario:

Mean pga~0.25g;

Higher than predicted by Ambraseys et al – 0.112g, but below the PrSD;

Strong motion duration is shorter ;

Analysis for controlling events



Time histories; Max and Min of pga

Mean pga ~ 0.297g,

Close to the prediction by Ambraseys et al (thrust faulting); **below the PrSD**

Strong motion duration significantly shorter

Final Seismic Design Basis

- The refined scenario-based SHA confirms the seismic design basis as derived from the “non-informed” SHA;
- Some probability that the design basis will be exceeded (according to simulation results)
- Seismic margins have to be evaluated by a seismic risk analysis;

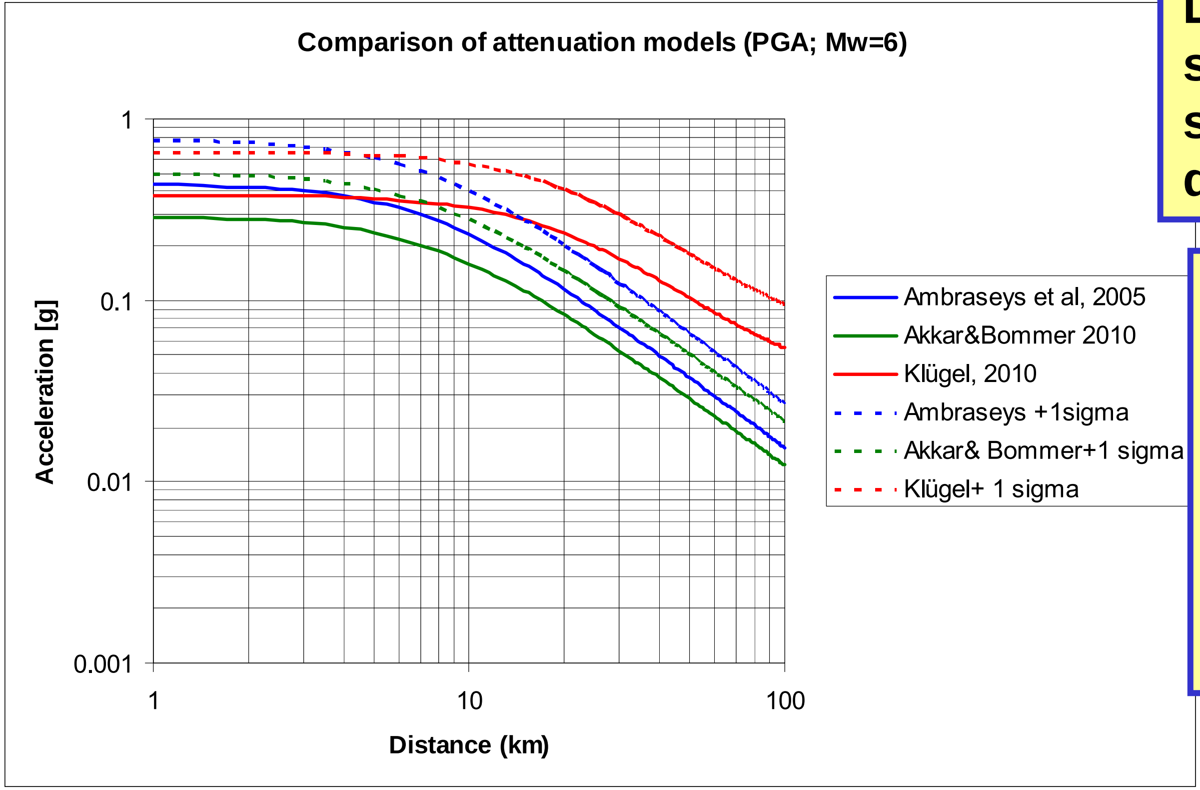
Seismic Risk Analysis

- Advanced seismic risk analysis should be scenario-based;
- Here a simplified approach is used, based on traditional PSHA and UHS;
  - For low seismic areas this is known to lead to conservative results (Klügel, 2009)
- Two cases:
  - Non-informed PSHA study
  - More informed study
- Degree of information (two correlated meanings):
  - How much use is made from site- or plant specific data
  - Measured information (mathematical definition according to information theory) - measure of the quality of a probabilistic model

PSHA Boundary Conditions

- Case 1:
  - using the “latest” empirical attenuation models (Akkar& Bommer 2010);
  - noninformative models for the distribution of seismicity within a seismic zone; seismic zonation from PEGASOS SP1 EG1a
  - truncated exponential G-R law;
  - hazard truncation at 3 sigma;
- Case 2:
  - Use of site-specific attenuation model (empirical equation developed from simulations)
  - Hazard truncation based on statistical data analysis
  - Lifetime of structure considered by truncating max magnitude values (based on theory of records) – it is very unlikely that the historical maximum magnitude observed over an observation period of 800 years will be exceeded during the lifetime of a short-lived structure (60 years)

Site-specific GMPE



Developed from 795 simulated response spectra, Mw=4.0 to 8.0, distance 1-200km

Directivity effect?

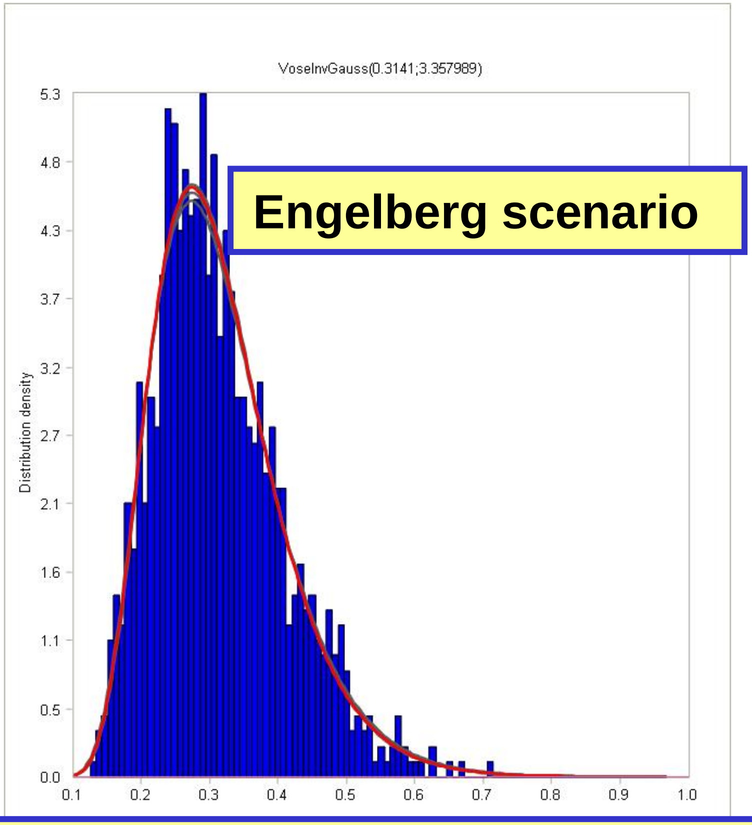
Reference points used for the Klügel model are from sources in North West direction of the site, one recording from a South East source would drop below the model

$$\log\left(PSA\right) = b_1 + b_2 M + b_3 M^2 + \left(b_4 + b_5 M\right)\log\sqrt{R_{jb}^2 + b_6^2} + b_7\sqrt{R_{jb}^2 + b_6^2}$$

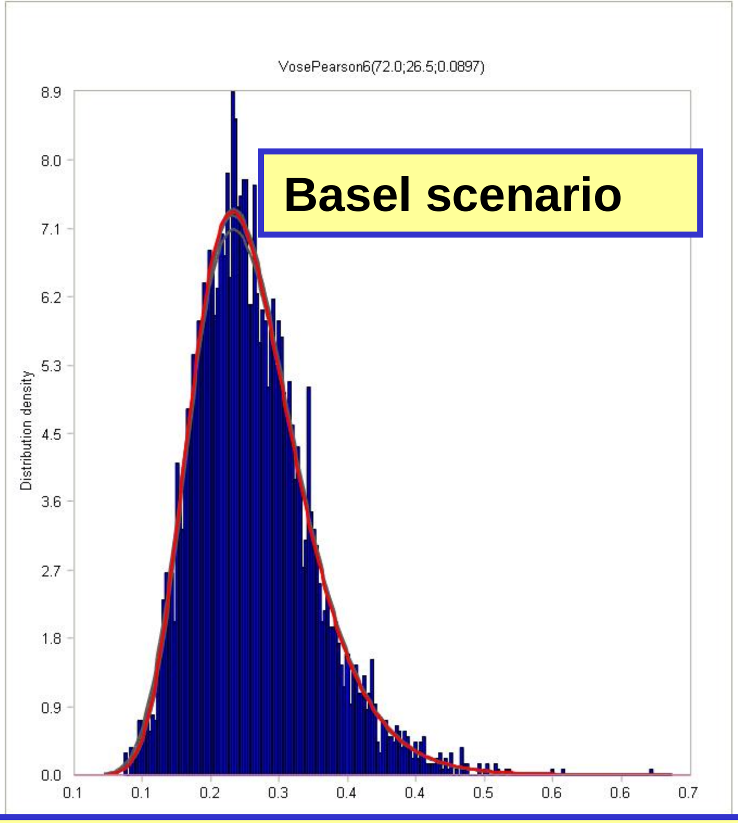
Data analysis

- Detailed statistical analysis performed on simulated data
- Parametric fit for the distribution of peak ground acceleration
  - based on information theory (weighted mixture of Akaike’s, Schwartz’ and Hannan-Quinn information criteria)
- Analysis did show that the lognormal distribution model is not the best performing model

Site-specific GMPE, Statistical data analysis from simulations



Engelberg scenario



Basel scenario

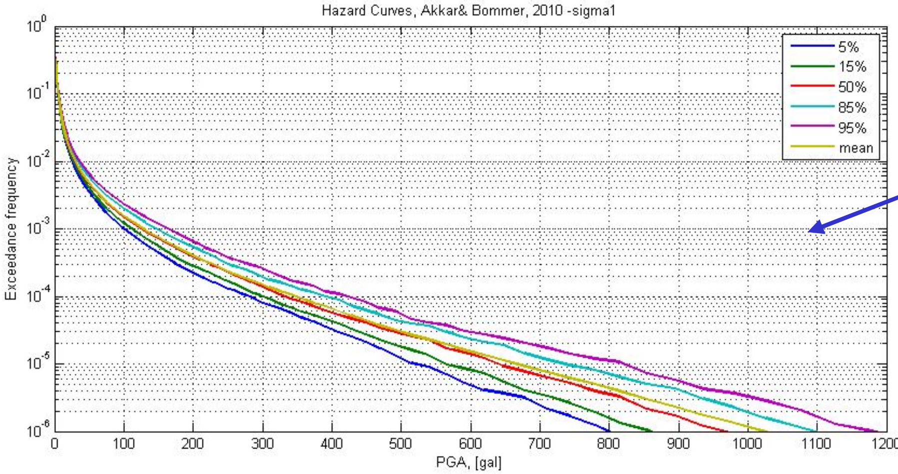
Ground motion levels from individual earthquakes are well constrained; truncation in PSHA model set to ca. 1.28 sigma

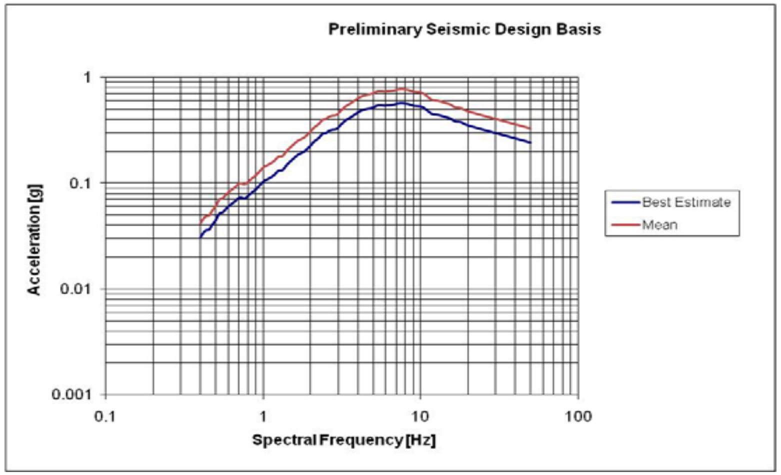
Insights from data analysis

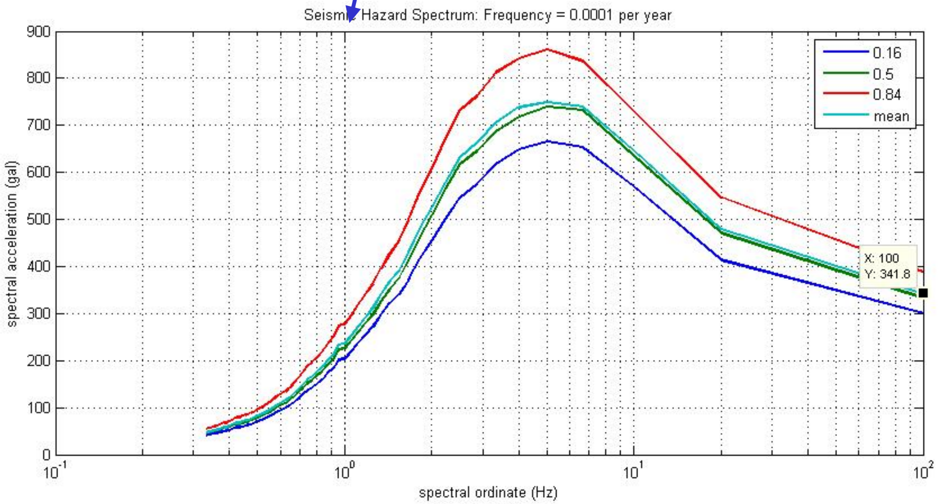
- Ground motion levels from individual earthquakes for a given site are well constrained
  - Corresponds to energy conservation principles
  - For constrained conditions the model of lognormal distribution is clearly rejected
- If each source for a given propagation path and for a given site generates constrained ground motion levels – why does the ensemble of earthquake data processed for the development of empirical GMPEs lead to very heavy upper tails of ground motion?
- The effect that analyses of the authors of empirical GMPEs lead to acceptance of the lognormal model is a result of data pooling – it is simply a reflection of the Central Limit Theorem in Logspace

PSHA-results case 1

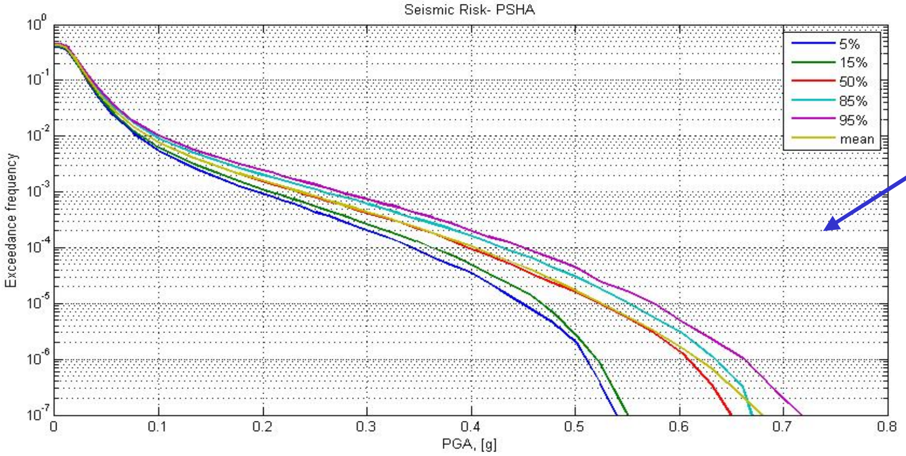
Hazard Curves and UHS for 10^{-4}/a, geometric mean



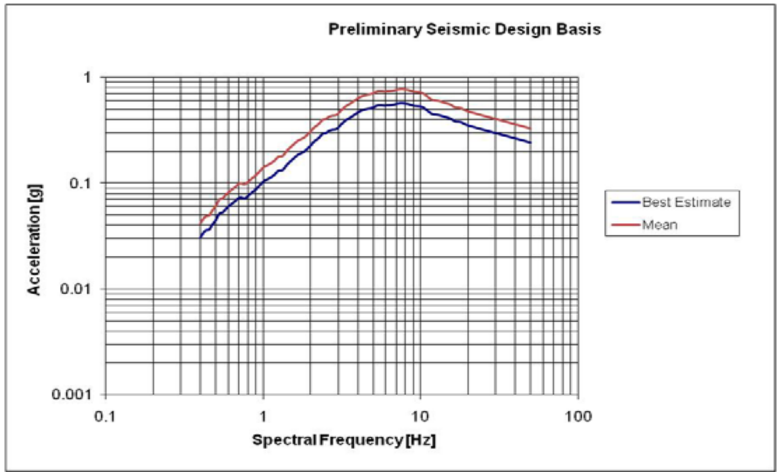


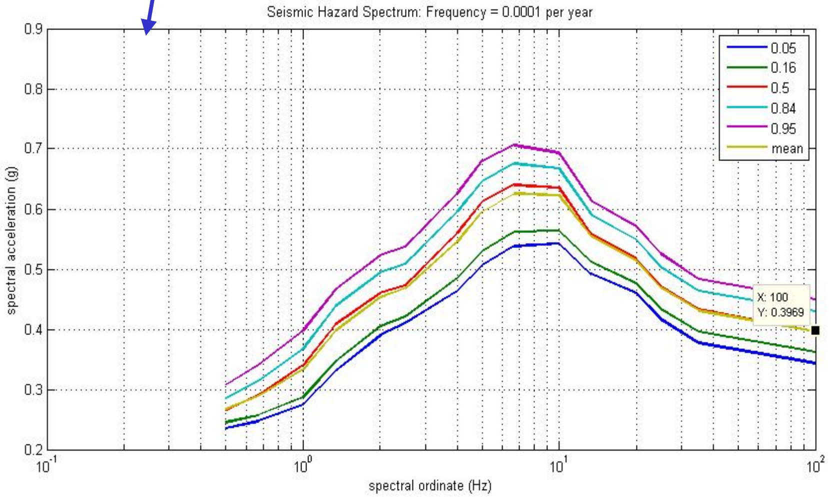


PSHA results case 2



Hazard Curves and UHS for 10^{-4}/a, larger horizontal component





Seismic Risk Analysis for NPP, Seismic PSA

- Case 2 was used as the probabilistic seismic hazard description
- Standard fragility approach was used, double lognormal distribution (no adjustment for the seismic input energy content as in Klügel, 2009)

$$f(\alpha) = \frac{1}{\sqrt{2\pi}\beta_U} \exp\left[-\frac{1}{2}\left\{ \frac{\ln(\alpha/C)}{\beta_R} \right\} \right]$$

α-Intensity (PGA)

C-Capacity (median)

Seismic Risk Analysis for NPP, Seismic PSA

- Design basis of 0.33g leads to a plant HCLPF (**H**igh **C**onfidence of **L**ow **P**robability of **F**ailure = 95% confidence of less than 5% failure probability) of 0.5g;
- According to IAEA requirements two independent seismically hardened safe shutdown trains are assumed; reliability of components (independent failures have to be accounted) corresponds to today's Goesgen data
- Computed seismic core damage frequency (CDF) is 1.09 x 10^{-6}/a – this is an acceptable value;
- A scenario-based approach would lead to a lower (more realistic) risk assessment

Summary and Conclusions

- A procedure for the development of the seismic design basis of critical infrastructures was presented (scenario-based approach)
  - Commensurate to the decision making process of investors
  - Simple to implement
  - Considers all relevant seismic sources treating all identified faults and distortions as seismic active
  - Leads to robust but economically acceptable results
  - Low seismic risk for the critical infrastructure installed (example of a new NPP)