The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

H4.SMR/1645-32

"2nd Workshop on Earthquake Engineering for Nuclear Facilities: Uncertainties in Seismic Hazard"

14 - 25 February 2005

Dealing with large uncertainties: maximum ground motion and physical limitations

Pierre-Yves Bard

LGIT/LCPC
Grenoble, France

Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

Dealing with large uncertainties: maximum ground motion and physical limitations

Pierre-Yves BARD

LCPC Paris / LGIT Grenoble

bard@obs.ujf-grenoble.fr

Tel:04 76 82 80 61

Outline

The issue

- low probabilities and lognormal GMPE
- Hopes to reduce σ ?
- Challenge : capping by upper bounds

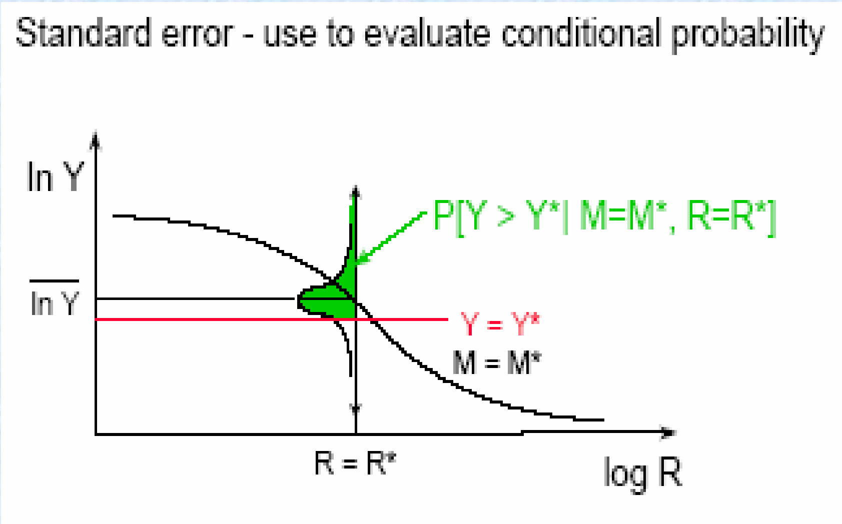
Looking for physical upper bounds

σ values and upper bounds

PSHA "Achille's heel"

- **Low annual probabilities : possibility of unphysical estimates**
  - Examples : PEGASOS (10^{-7}), Yucca Flat (10^{-8})
- **Origin :**
  - M, R always physically possible
  - but
  - tail of Gaussian distribution on GMPE : no upper limits for $\varepsilon\sigma$
    - ε = 1 : 84%; ε = 2 : 97.7%; ε = 3 : 99. %; ε = 4 : 99.%;
  - ⇒ no saturation of hazard estimate
  - ⇒ hazard driven by the tail of the lognormal distribution of residuals
- **Common, artificial solution**
  - truncating ε to some values (2, 3) : convenient, but not satisfactory

Aleatory variability in GMPE



GMPE : distribution of residuals : ? lognormal ?

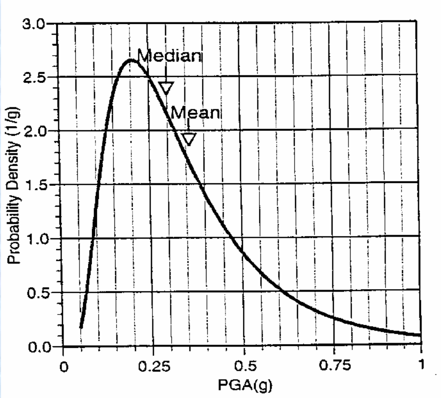


Figure 3. Comparison of the mean and median for a lognormal distribution with a standard deviation of 0.6.

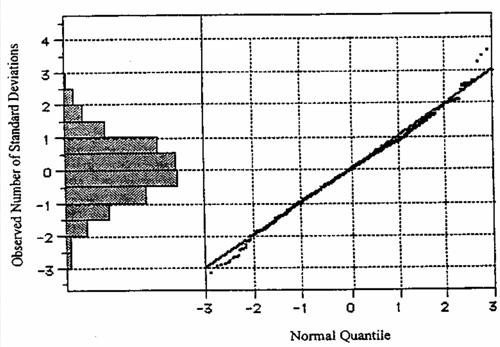
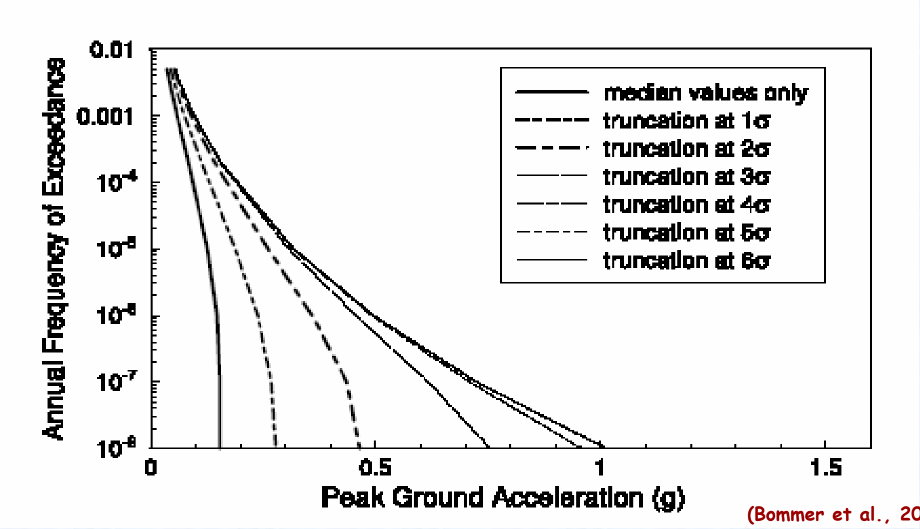


Figure 4. Normal quantile plot comparing the observed distribution of peak accelerations with the assumed lognomral distribution. If the data follow a lognormal distribution, the points would lie on the line.

D'après Abrahamson, 2000

Effects of uncertainties and truncation in attenation relationships

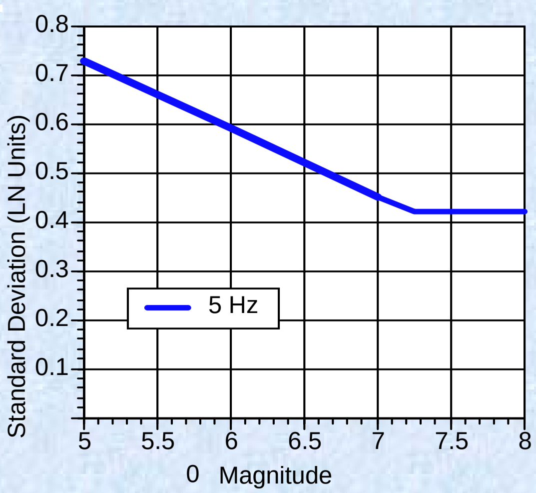


(Bommer et al., 2004)

Aleatory variability σ in GM predictive equations

- larger data sets: equal σ !
- almost no hope of significant reduction of σ in the foreseeable future
  - (complexity of physics, crudeness of models)
- homoskedastic or not ?
  - variability of σ with M, or R, or pga, or site conditions
  - Partial results
    - σ ↘ when M ↗
    - σ ↘ when R ↘
    - σ ↘ when pga ↗
    - σ ↘ when site softness ↗

Standard Deviation of Ground Motion



σ values and upper bounds

Does DSHA provide envelope estimates ?

Pessimistic scenarios (M, R) but

Median : 50 % chances to be exceeded

Median + σ : 16% chances to be exceeded (1 in 6 !)

Answer = NO !

Outline

The issue

- low probabilities and lognormal GMPE
- Challenge : capping by upper bounds

Looking for physical upper bounds

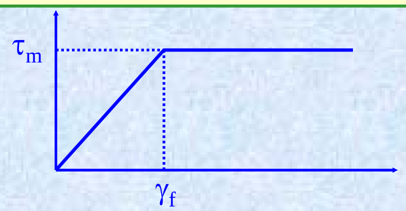
- source properties ?
- path characteristics ?
  not easy : very high levels (> 5 g) could not be proved to be unphysical!
- site characteristics ?

STRAIN APPROACH (Betbeder, Pecker)

Represent the soil constitutive behavior by an elastic perfectly plastic law

Requires only two parameters to define the behavior, τ_m and γ_f

$$\tau_{max} = \sigma'_v \tan(\varphi') + c'$$



G is equal to τ_m/γ_f ,

Damping ratio needs to be assessed independently; a value of 20% is considered

BETBEDER MODEL

the shear modulus is constant with depth (p=0)

the constitutive law for the soil is represented by the hyperbolic model, G_{max} and γ_r

the average soil column acceleration is limited by the available shear strength τ_{max} :

$$\rho\, h\, A_m \le \tau_{max} = \rho\, V_s^2\, \gamma_r$$

computation of a fundamental "non linear" mode shape of the soil column to relate A_m to A_{max}

$$\ddot{u}_{max} \le 2\frac{V_s^2\, \gamma_r}{h}$$

$$2\left(\frac{\ddot{u}}{\ddot{u}}\right)^2 = 0.25 + 2\left(\frac{\ddot{u}}{\ddot{u}_{max}}\right)^2$$

RESULTS

	GÖSGEN	MÜHLEBERG	BEZNAU	LEIBSTADT
Surface	11.6	10.4	6.0	12.9
pga rock	infinite	infinite	infinite	infinite

Pecker's mechanical approach Hz1

Basis

- Estimating the depth dependent shear strength (Cu, φ)
- Estimating the yield shear strain (2-3 %)
- Assumptions
  - ⇒ Velocity gradient $(z/h)^p$ + large damping (20%)
  - ⇒ 3 modes for modal summation
  - ⇒ given shape for a normalized input spectrum (EC8)
- Modal representation of soil response → upper bound for pga
  - ⇒ determining the depth z_y where the strain is maximum
  - ⇒ determining the scaling factor for input spectrum to reach, at this z_y depth, the 3% yield strain
  - ⇒ computing the corresponding surface acceleration from modal summation
- Spectral shapes then derived from "linear" 1D computations with "yield" parameters

MAXIMUM GROUND MOTION

Two different approaches:

- A theoretical model:
  - Specifically developed for this study (GDS model)
- Use of non linear site response analyses
  - Plot $\overline{m} + 2\sigma$ of the ground surface acceleration as a function of rock input acceleration and extrapolate

Validation of the theoretical models:

- Real site with strong recordings (Rosrine SMT site)

GDS THEORETICAL MODEL

$$\frac{\partial \tau(z)}{\partial z} = \rho \frac{\partial^2 u}{\partial z^2} \quad , \quad \tau(z) = G(z)\frac{\partial u}{\partial z}$$

$$G(z) = G_0\left(\frac{z}{H}\right)^p \quad , \quad V(z) = V_0\left(\frac{z}{H}\right)^{\frac{p}{2}}$$

$$\frac{\partial^2 u}{\partial z^2} + \frac{p}{z}\frac{\partial u}{\partial z} - \frac{1}{V_s^2}\left(\frac{h}{z}\right)^p \frac{\partial^2 u}{\partial t^2} = \frac{1}{V_s^2}\left(\frac{h}{z}\right)^p \frac{d^2 v_g}{dt^2}$$

Boundary conditions:

$$\lim_{z \to 0} G(z)\frac{\partial u}{\partial z} = 0$$

$$u(h) = 0$$

$$u = X(z)\,e^{i\omega t} \quad \Rightarrow \quad X = A\,z^{\frac{1-p}{2}}\,J_{\frac{p-1}{2-p}}\left[\frac{2\,\omega\,h^{\frac{p}{2}}}{V_s\,(2-p)}\,z^{\frac{2-p}{2}}\right]$$

Eigenfrequencies:

$$X(h)=0 \quad \Rightarrow \quad J_{\frac{p-1}{2-p}}\left[\frac{2\,\omega\,h}{V_s\,(2-p)}\right]=0 \qquad f_i = \rho_i\,\frac{V_s\,(2-p)}{4\pi\,h}$$

$$u(z,t) = \sum_{i=1}^{n} X_i(z)\,Z(t) \qquad X_i(z) = \begin{cases} \cos\left(\dfrac{\omega_i z}{V_s}\right) & p = 0 \\ J_\nu\left(\dfrac{\omega_i z}{V_s}\right) & 0 < p < 2 \end{cases}$$

Maximum ground surface acceleration

$$u_i(z) = \alpha_i\,S_d(\omega_i,\xi_i)\,X(z)$$

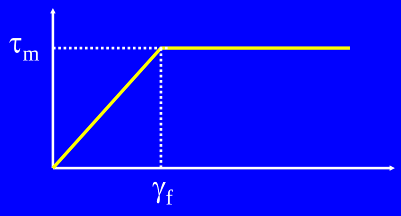
$$\ddot{u}_{max}(z=0) = \left[\sum_{i=1}^{N}\left(\alpha_i\,S_a(\omega_i,\xi_i)\right)^2\right]^{\frac{1}{2}}$$

Shear strain attributed to fundamental mode:

$$\lambda(z) = \frac{\gamma(z)\,\omega_1^2}{S_a(\omega_1,\xi_1)} = \alpha_1\left(\frac{2}{a}\right)^{\nu}\Gamma\left(\frac{1}{2-p}\right)\left\{(1-p)\,z^{-\frac{p+1}{2}}\,J_\nu\left(a\,z^{\frac{2-p}{2}}\right) + a\,\frac{2-p}{2}\,z^{\frac{1-2p}{2}}\,J_{\nu-1}\left(a\,z^{\frac{2-p}{2}}\right)\right\}$$

STRAIN APPROACH

- Represent the soil constitutive behavior by an elastic perfectly plastic law



Requires only two parameters to define the behavior:

τ_m and γ_f: $\tau_{max} = \sigma'_v \tan(\varphi') + c'$

G is equal to τ_m/γ_f , the damping ratio needs to be assess independently; a value of 20% is considered

PROCEDURE

1. define the input motion at the rock interface by its pseudo acceleration response spectrum Sa*.

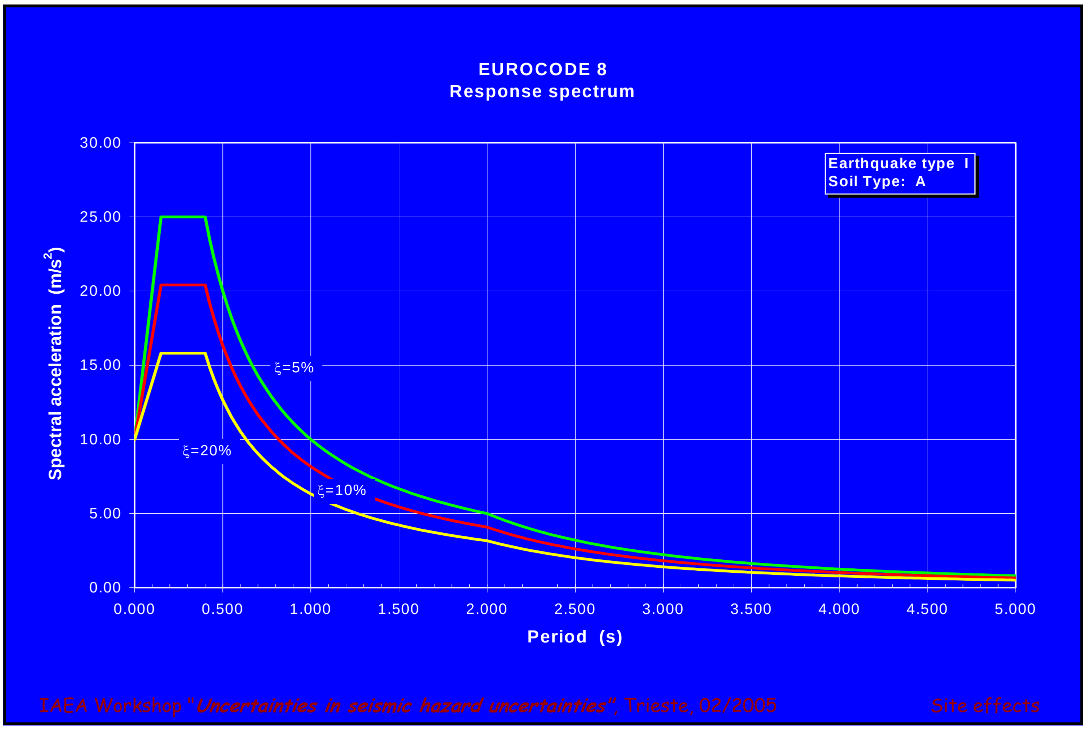
2. compute the eigenfrequencies and mode participation factors

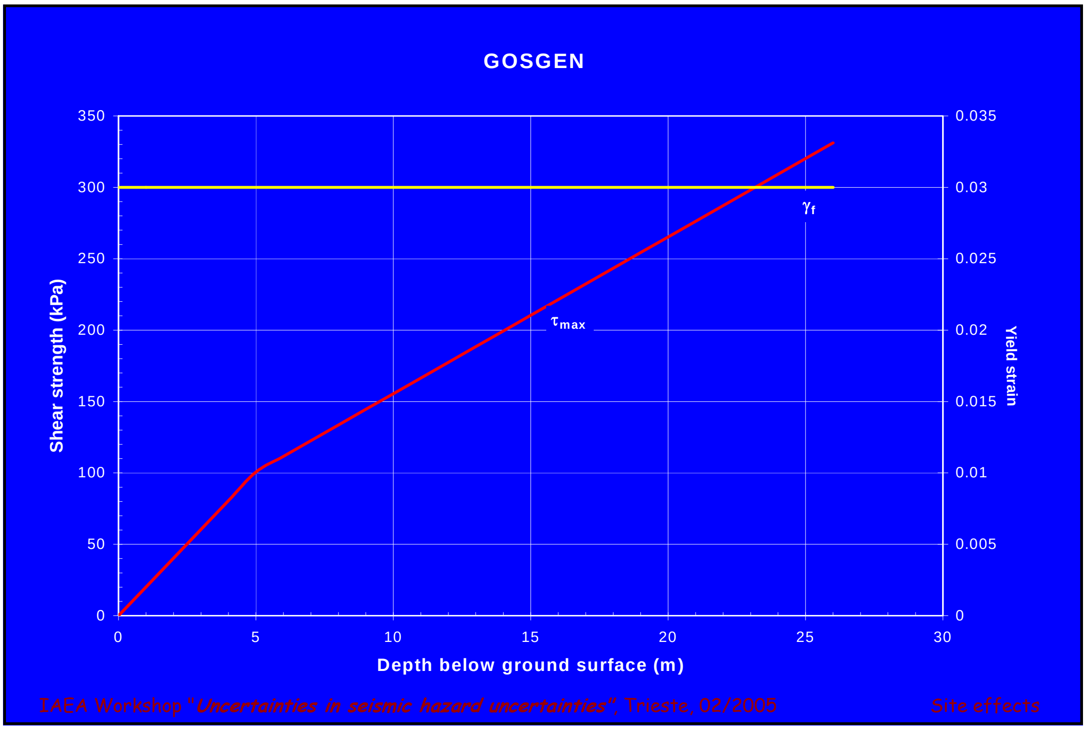
3. plot the normalized shear strain versus depth together with the yield strain γ_f.

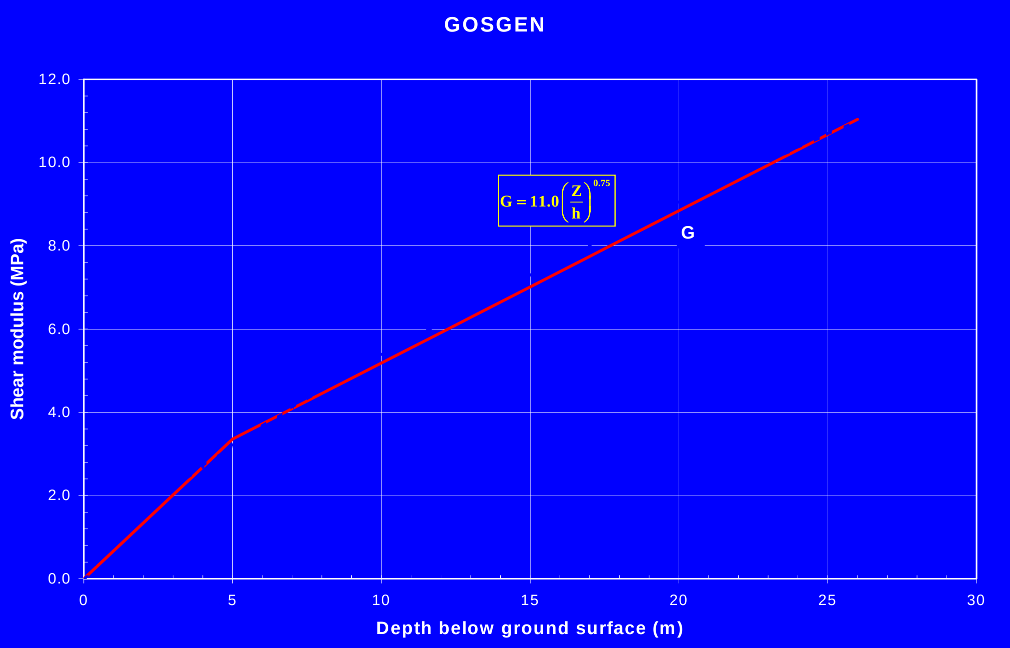
4. determine the depth z_0 and the scaling factor μ for which

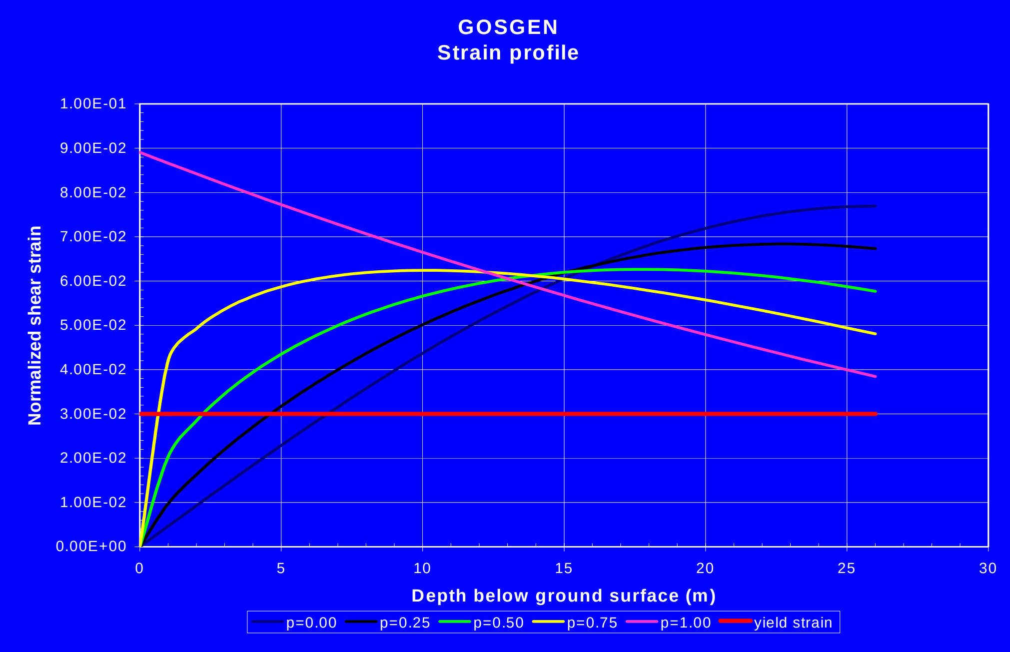
$$\gamma_f = \mu \frac{S_a^*}{\omega_1^2} \lambda(z_0)$$

5. define $Sa = \mu \ S_a^*$ the maximum possible pseudo acceleration from which the maximum ground surface acceleration $\ddot{u}_{max}(z=0)$ is determined


EUROCODE 8
Response spectrum
Earthquake type I
Soil Type: A
Spectral acceleration (m/s²)
ξ=5%
ξ=10%
ξ=20%
Period (s)
IAEA Workshop "Uncertainties in seismic hazard uncertainties", Trieste, 02/2005
Site effects


GOSGEN
Shear strength (kPa)
Yield strain
γf
τmax
Depth below ground surface (m)
IAEA Workshop "Uncertainties in seismic hazard uncertainties", Trieste, 02/2005
Site effects





IAEA Workshop "*Uncertainties in seismic hazard uncertainties*", Trieste, 02/2005 Site effects

RESULTS FOR GÖSGEN

$\omega_1 = 3.51$ rd/s , $f_1 = 0.56$ Hz
$\omega_2 = 8.92$ rd/s , $f_2 = 1.42$ Hz
$\omega_3 = 14.03$ rd/s , $f_3 = 2.23$ Hz

↓

$S^*_{a1} = 3.54\ m/s^2$ $S^*_{a2} = 8.98\ m/s^2$ $S^*_{a3} = 14.12\ m/s^2$

$\mu = 1.67$

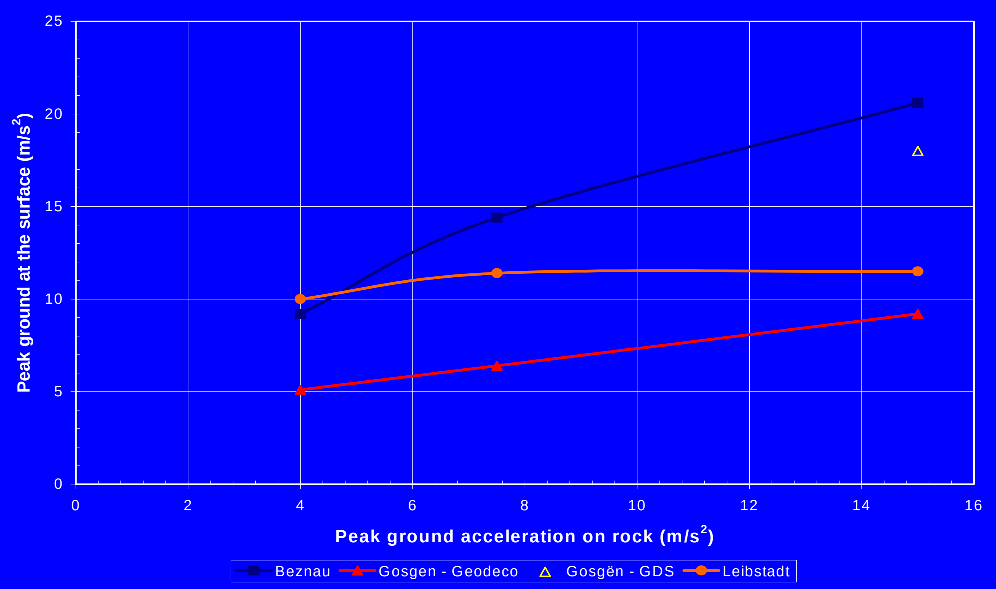
$S_{a1} = \mu S^*_{a1} = 5.91\ m/s^2$

$S_{a2} = \mu S^*_{a2} = 15.00\ m/s^2$

$S_{a3} = \mu S^*_{a3} = 23.58\ m/s^2$

$\ddot{x}_{max} = 19.6\ m/s^2$

NON LINEAR SITE RESPONSE ANALYSES



ROSRINE SITES

- Only one site has similar depths and soil characteristics:
  ⇒ SMT site
- Soil profile: 31m of "rock-gravel"
- Rock depth and shear wave velocity unknown
  ⇒ impedance ratio
- Water table depth ?
  ⇒ taken at base of soil column (based on moisture content and P wave velocity)

RESULTS

GDS model:

- $17.5\ m/s^2 \leq amax \leq 29\ m/s^2$

Betbeder model:

- $amax = 6.7\ m/s^2$

Observed:

- $amax = 8.9\ m/s^2$
- (Superstition Hill, $M_w = 6.5$, d = 8 km)

IAEA Workshop "*Uncertainties in seismic hazard uncertainties*", Trieste, 02/2005 Site effects

TENTATIVE PROPOSALS

Gösgen : 17 m/s^2

Mühleberg : 25 m/s^2

Beznau : 20 m/s^2

Leibstadt : 15 m/s^2

Mechanical approach (Pecker's) Hz1

Personal assessment

Pros :

- the only "site-specific" approach
- A sound mechanical basis

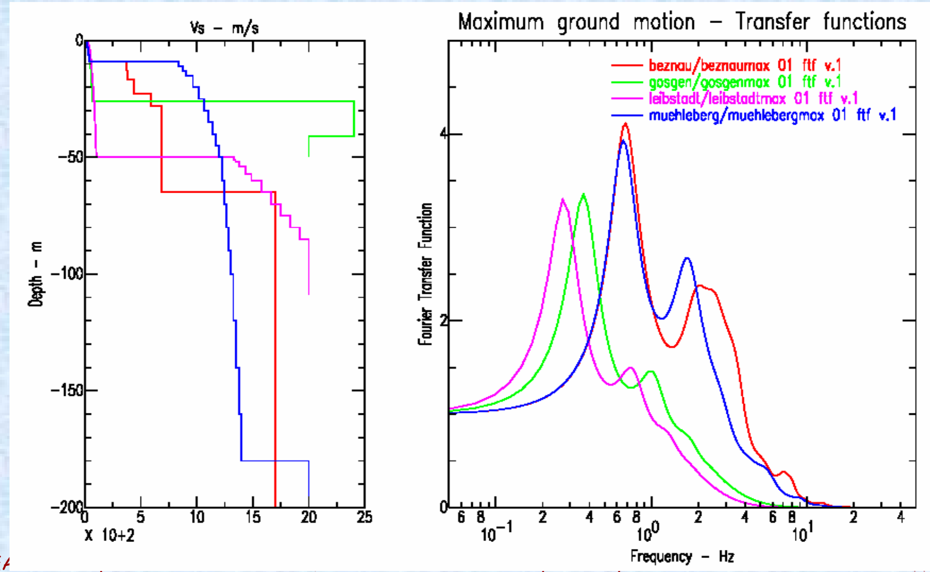
Cons: a few "troublemaking" assumptions

- ⇒Vs(z) : power law dependence at failure: no strain localisation
- ⇒Yield strain : similar for dynamic and static loads ???
- ⇒Modal approach still valid at failure ???

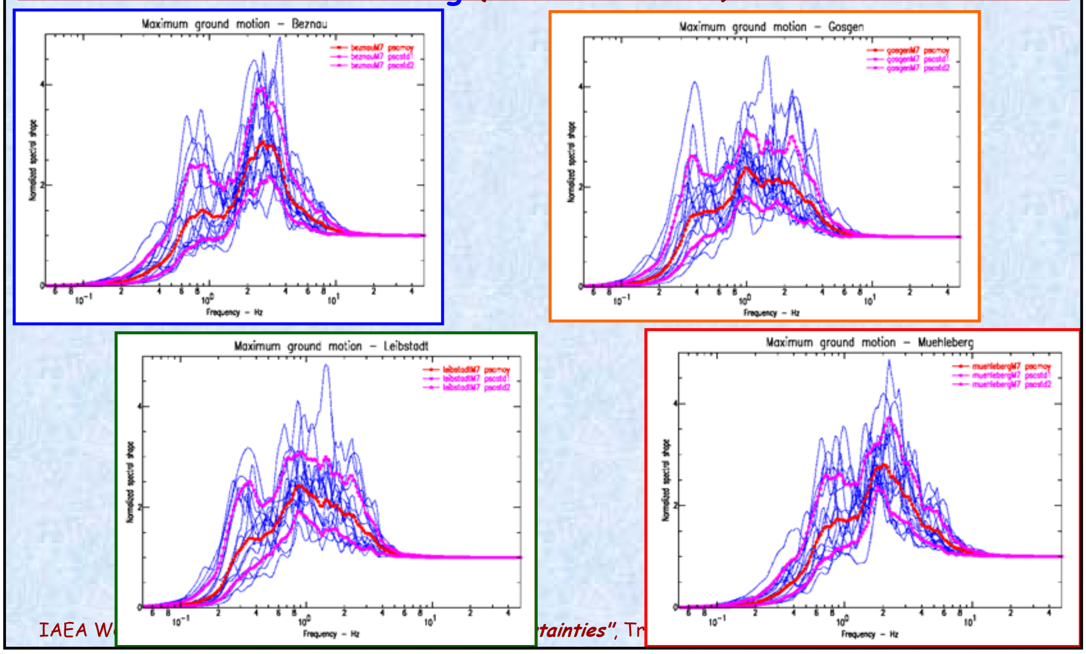
Consequences

- ⇒Limited confidence in the numerical values : subbranching to account for the epistemic uncertainty

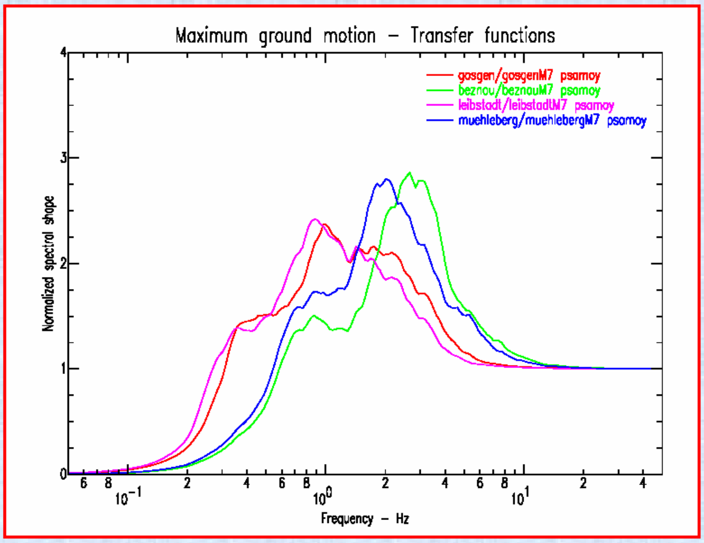
Velocity profiles and Fourier transfer functions for the 4 sites under "extreme" loading (from TP3-TN-0358)



Normalized response spectra for the 4 sites under "extreme" loading (from TP3-TN-0358)



Comparison of the average normalized spectra for the 4 sites



Empirical approach (Fäh's) Hz2

Basis

Maximum ever recorded spectral ordinate at each frequency

Site categorization through 4 site classes : "soil"

Personal assessment

Pros

⇒Free of any underlying model and assumption

⇒Actual data

Cons

⇒ Very poorly related with actual site conditions

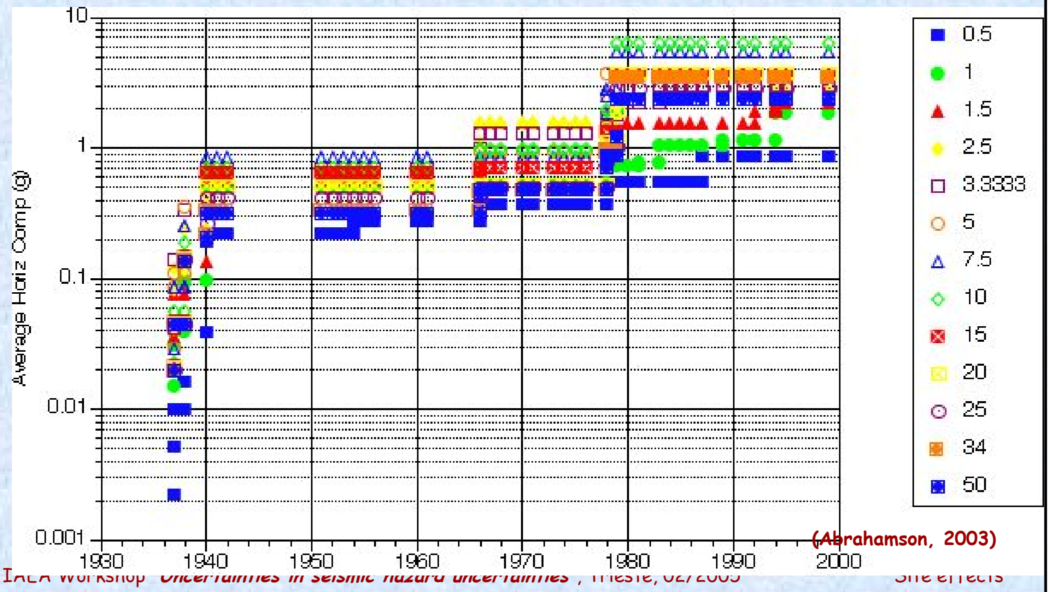
⇒ Lower bound estimates : by how much ?

Consequences

⇒ Subbranching to account for the fact that "ever recorded maximum" can only increase in the future

⇒+ enveloping / smoothing the observed spectra

Temporal evolution of maximum observed ground motion



Max horizontal and vertical spectra

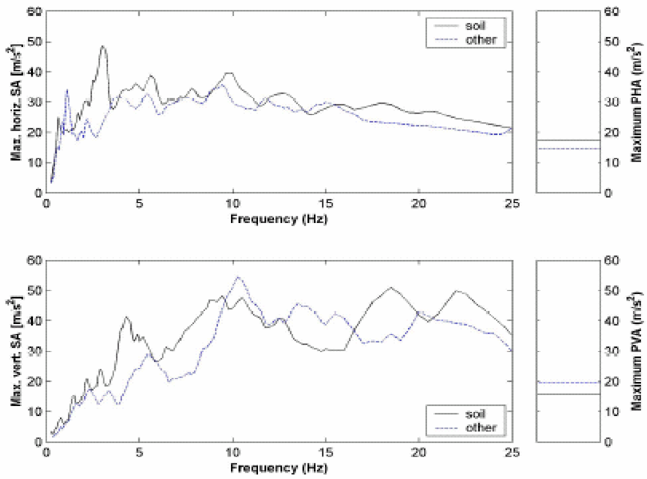
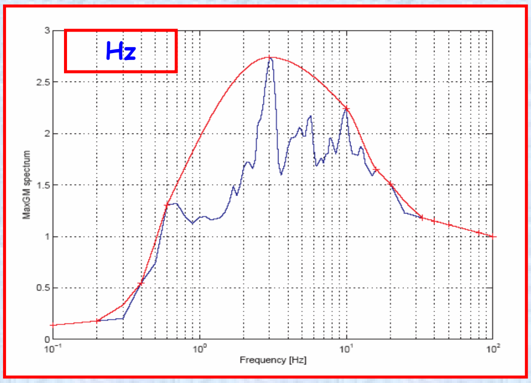


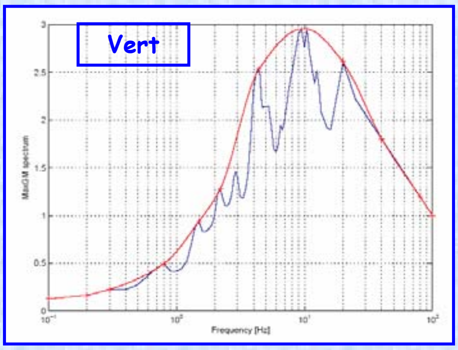
Figure 3: Maximum spectral acceleration and maximum peak acceleration of all the records. Top: Maximum horizontal SA and maximum peak horizontal acceleration (PHA). Bottom: Maximum vertical SA and maximum peak vertical acceleration (PVA). Solid black line: local geology is "stiff soil", "soft soil" or "alluvium". Dashed blue line: local geology is "rock", "very soft soil" or unknown.

Maximum recorded spectra Hz3

Observed spectra

- Peaks and troughs : no physical reasons leading to spectral values rapidly varying with frequency
- Enveloping and smoothing based on observed local maxima





Logic tree structure + weights Hz4

Pecker's mechanical approach = 50%

- Uncertainty in pga values
  - Base pga values :

Site	Beznau	Gösgen	Leibstadt	Mühleberg
Pga (m/s²)	x	y	z	T

- Subbranching into 4 branches
  - Applying scaling factors to these pga values

Multiplication factor	0.707	1.0	1.414	2.0
Weights	a%	b%	c%	d%

- Associated spectra : 2 branches
  - Normalized spectral shapes from linear computations (TP3-TN-0358)
    - u%
  - Normalized spectra from existing SM records (soil, TP3-TN-0359)
    - v%

Logic tree structure and weights

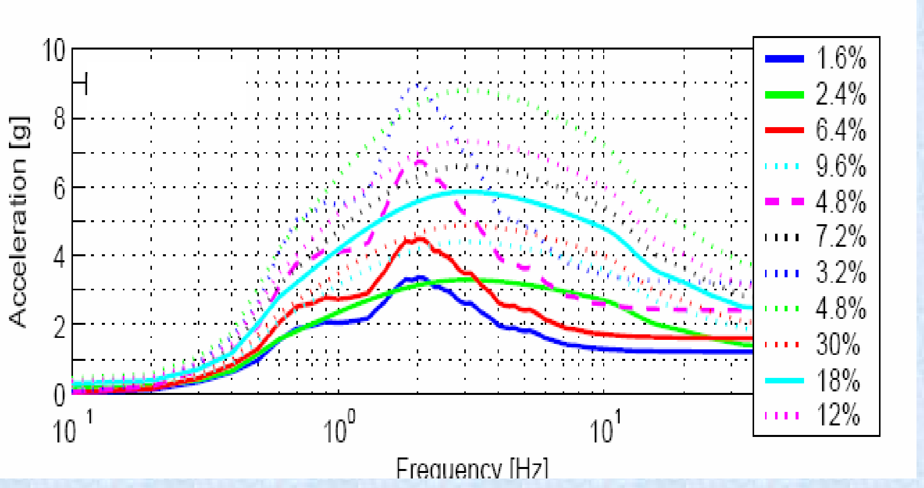
Hz5

Fäh's empirical approach = 50%

- Lower bound estimates → 4 branches
  - 4 multiplication factors ≥ 1

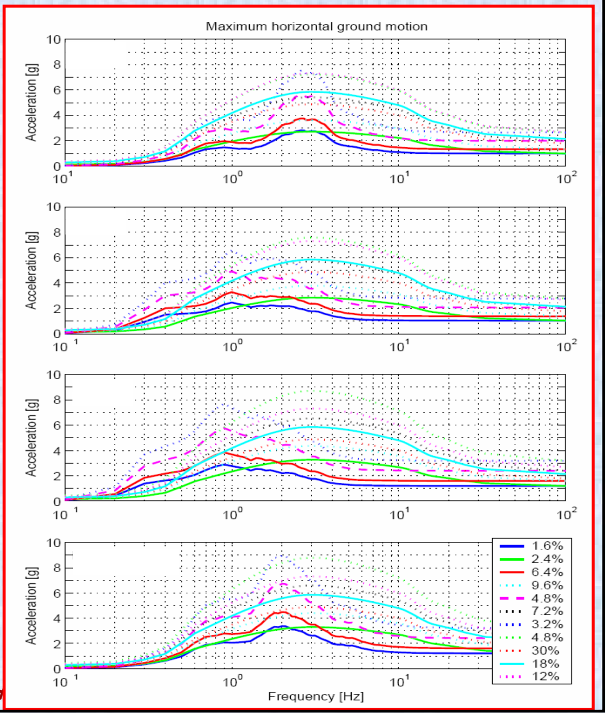
Multiplication factor	1.0	1.2	1.5	2.0
Weights	xx%	yy%	zz%	tt%

Site specific estimate of maximum ground motion



Final results for Hz motion

Hz7



Vertical component

V1

Basis

No limitation related to soil behavior

⇒(except possibly for downgoing motion)

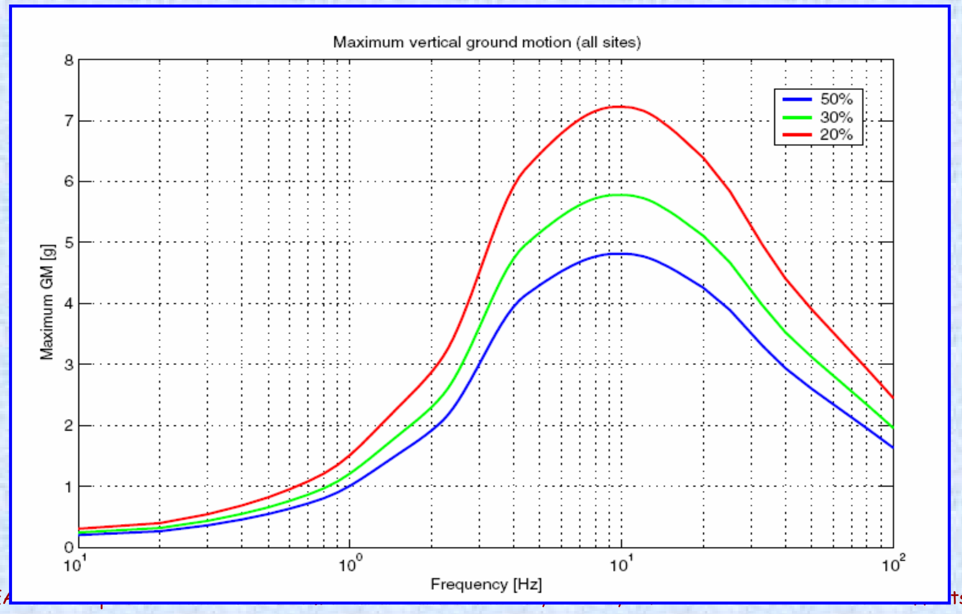
Only Fäh's empirical approach = 100%

Logic tree and weights

- Lower bound estimates → 2 branches
  - 4 multiplication factors ≥ 1

Multiplication factor	1.0	1.2	1.5	2.0
Weights	a%	b%	c%	d%

Final results for vertical motion V2



Concluding comments

Bounding through site effects / soil strength

- Physically sound
- this first approach is still very crude
  - (velocity gradient, modal approach, no strain localization
  - worth being refined and investigated with truly non-linear models (which should be able to handle that issue in a more satisfactory way)
- Not valid for the vertical component

Bounding based on empirical data

- ? composite spectrum (maxima coming from different records for each frequency)
  (Analog to "Uniform Hazard Spectrum")
- Put instruments on soft sites close to very active, long faults to check the models and get more "site-specific" upper bounds

Bounding based on source / path physics

- still to be done !