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ON THE INFLUENCE OF SEDIMENTS ON THE SHAPE OF RESPONSE SPECTRA

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SUMMARY

For the greater area of the city of Cologne a microzonation from an earthquake engineering perspective was introduced. The area has been divided into 8 subregions with approximately uniform soil profile. For all regions the influence of the sediments on simulated earthquakes has been investigated by three well known methods: 2-layer solution, SHAKE 91, HASKELL matrix algorithm. The transfer functions and response spectra were computed and compared to the elastic acceleration response spectra of the draft of the new German building code E-DIN 4149. Two different methods for the generation of synthetic accelerograms and the three dynamic analysis procedures have been compared and a series of issues relevant to the practical application of them were discussed.

INTRODUCTION

The city of Cologne is situated in the Lower Rhine Embayment – one of the most seismic regions in Germany. In the framework of the German Research Network for Natural Disasters (DFNK) - an interdisciplinary and interinstitutional research project on natural disasters (earthquakes, floods, storms and forest fires) - one subproject was related to the investigation of site effects of earthquake shaking (microzonation). The goal of the Geotechnical Institute of the TU Berlin was the proposal of an easy-to-use zonation of the area of Cologne for the practical earthquake engineer, which might be used for supplementary earthquake hazard studies that more precisely account for the local geology than the new German building code E-DIN 4149. Included in this work was a comparison of 2 methods for the simulation of earthquakes (SIMQKE; Boore [1]) and of 3 methods for wave propagation analysis in sedimentary layers (2-layer model, SHAKE, HASKELL algorithm). All these methods have been applied to a developed geophysical model of the city of Cologne. The results of the calculations were compared with in-situ measurements of the predominant ground frequency and with the elastic acceleration response spectra of the draft of the new German Building Code E-DIN 4149.

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GEOLOGICAL SETTING AND THE PROPOSED MICROZONATION

The larger area of Cologne is situated in the Lower Rhine embayment – a strongly fractured Graben system with SE-NW trending faults. The geology of the area consists of a soft sedimentary cover of Tertiary and Quaternary age (mainly clays, sands and gravels) over hard Devonian rocks (limestone, Grauwacke and slates). The surface of the Devonian bedrock underneath the soft sediments has a trough like shape which is oriented from NE to SW. Moreover the bedrock surface is descending from the outcrop in the NE (Bergisch Land) of the investigated area to a depth of about 400 m in the SW, whereby the descent is due to several abrupt elevation changes along the above mentioned faults and also to a tilt of the individual blocks towards SW. In the view of an earthquake engineer the described geology represents in a simplified way a 2-layer system: a soft sedimentary layer over the hard bedrock.
For the microzonation of the area two aims had to be met: the different subregions should each be characterized by a uniform soil profile which can be used for earthquake engineering analysis, and secondly the analytical error that is induced by the assignment of a uniform bedrock depth to each region where in reality the bedrock surface changes gradually should be quantitatively assessable. As the impedance ratio ($\rho_2 v_{s2}/\rho_1 v_{s1}$) between the bedrock and the sediments and the thickness d of the sedimentary cover play the most important role for the amplification of the incident earthquake waves, it was decided to use the thickness d of the sediments as the main parameter for the determination of the individual subregions.
In order to assess the analytic error due to the constant thickness of the sediments in each subregion the following reasoning may be used: The influences that the sedimentary layers exert on incident earthquake waves are mathematically described by the transfer function T(ω) which relates the Fourier spectrum of the displacements on the ground surface S(ω) to the Fourier spectrum of the incident wave A(ω),

$$S(\omega) = T(\omega)\cdot A(\omega) \qquad (1)$$

The analytic solution for the transfer function of an elastic layer over an elastic halfspace can be found in Murphy [2]:

$$\left|T(\omega)\right| = \frac{2}{\left[\cos^2\left(\omega d / v_{s1}\right) + \left(\dfrac{\rho_1 v_{s1}}{\rho_2 v_{s2}}\right)^2 \sin^2\left(\omega d / v_{s1}\right)\right]^{1/2}} \qquad (2)$$

where ω is the circular frequency of the incident wave; d, ρ_1, v_{s1} are the thickness, the density and the shear wave velocity, respectively, of the sedimentary layer and ρ_2 and v_{s2} are the density and shear wave velocity of the bedrock (halfspace). The maximum amplitude amplification occurs for all those frequencies f_k for which the cosine term equals zero:

$$f_k = \left(\omega / 2\pi\right) = \frac{v_{s1}}{4d}\left(2k+1\right) \qquad (3)$$

where k = 0, 1, 2, … . The absolute value of the transfer function then equals the impedance ratio ($\rho_2 v_{s2}/\rho_1 v_{s1}$) multiplied by the free surface factor 2. Considering the frequency f_k in equation (3) as a function of the thickness d, it is possible to estimate the error that is induced by a difference Δd of the layer thickness to the resonance frequencies f_k of the sediments. Expanding (3) into a Taylor series and neglecting all terms with orders greater or equal 2 we find:

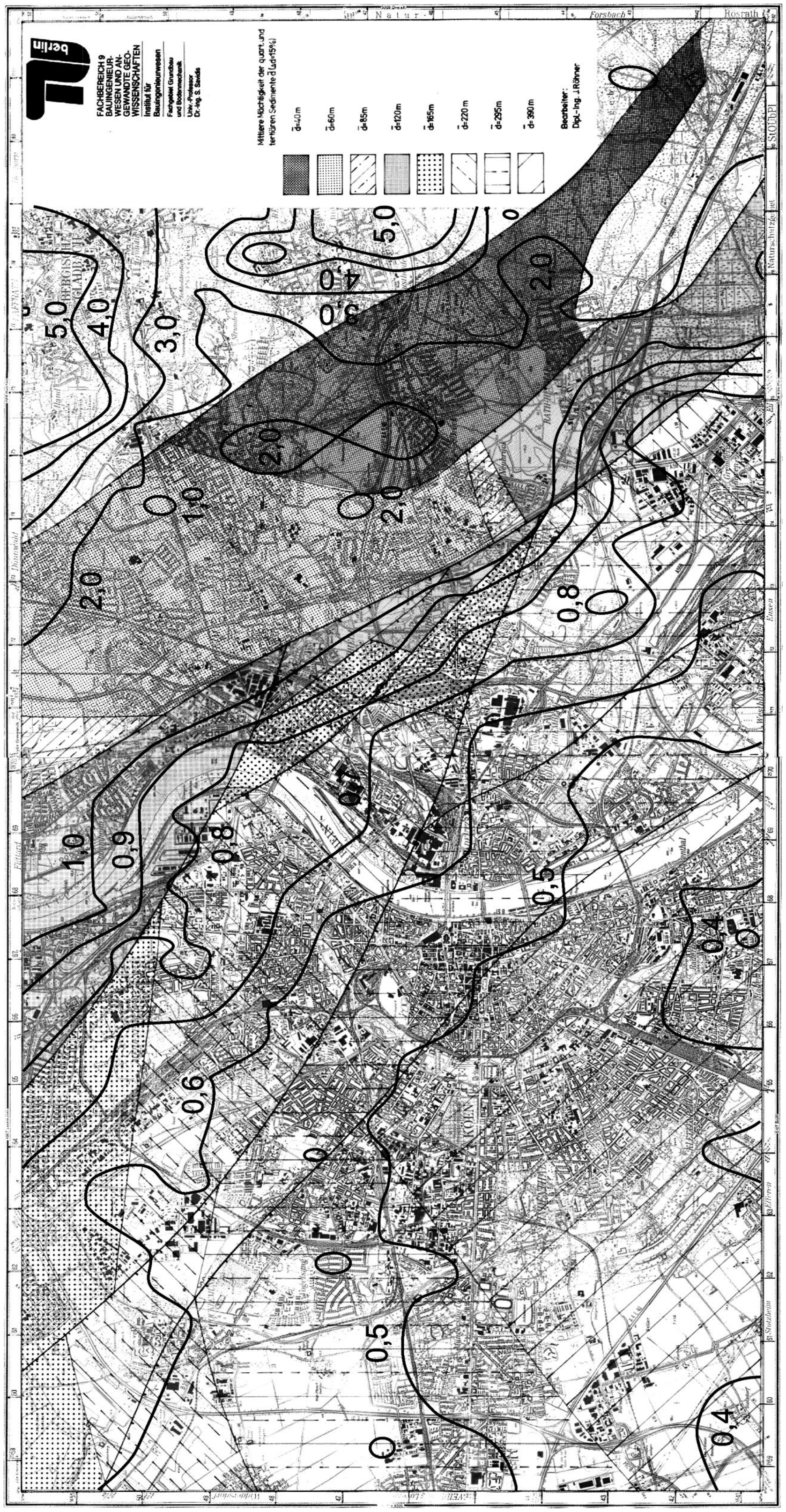

Figure 1: Microzonation of the Cologne area, superimposed are the isolines of the fundamental resonance frequencies in Hz as determined in-situ by Parolai [3]

$$f(d+\Delta d) \approx f(d) \cdot \left(1 - \frac{\Delta d}{d}\right) \tag{4}$$

Thus a change of the thickness d of $\Delta d/d = 20\%$ causes also a change for the resonance frequencies of $\Delta f_k/f_k = 20\%$. Due to this fact the Cologne area was divided into 8 subregions (Fig. 1) with average heights $\overline{d}$ of the sedimentary cover of $\overline{d}$ = 390, 295, 220, 165, 120, 85, 60 and 40 meters assuring that the fundamental resonance frequencies would not deviate more then about 15% from the average value.

SIMULATED EARTHQUAKE EVENTS

One of the aims of the TU Berlin research group was to elaborate the differences in the response spectra (5 % damping) that arise from a more accurate modeling of the sedimentary cover in the area of investigation in comparison to the new E-DIN 4149 building code. That is why it was decided to use simulated earthquake events that match in size the standard earthquakes of the E-DIN 4149, which have an average return period of 475 years. According to the E-DIN 4149 and the "Beiblatt 1" of the 'old' DIN 4149 Cologne belongs to the earthquake zone 2, to which Schneider [4] assigns the following standard events:

1. **Liege, 08. Nov. 1983**: focal depth h_0 = 6 km; moment $M_0 = 10^{16}$ Nm; stress drop $\Delta\tau$ = 1.6 – 2.5 MPa
2. **Roermond, 13. Apr. 1992**: focal depth h_0 = 15 km; moment $M_0 = 6.5\ 10^{16}$ Nm; stress drop $\Delta\tau$ = 2.5 – 4.1 MPa

With Gauss – distributed stress drops of $\Delta\tau = 2.0 \pm 0.4$ MPa (Liege) and $\Delta\tau = 3.3 \pm 0.8$ MPa (Roermond) synthetic earthquakes were produced using the program SIMUL (Langer [5], Kunze [6]). SIMUL generates synthetic accelerograms according to the stochastic method for the simulation of high – frequency ground motion as suggested by Boore [1] and lately reviewed by Lam [7]. Figure 2 depicts the 50% - fractile of 50 generated response spectra based on the resultant ground acceleration at the bedrock surface (outcrop) for both standard events. They are compared to the 50% - fractile elastic acceleration response spectrum for rock (soil class A1) of the E-DIN 4149. As the latter spectrum represents only one horizontal component of the ground motion, it was scaled by $\sqrt{2}$ to account for the resultant ground motion. Because the E-DIN spectrum has to cover a broad range of possible earthquakes it is not surprising that the spectra of the standard events do 'match' in their maximum values, however deviate in frequency content.

In engineering practice the response spectra of the building code are often used to generate artificial earthquakes for instance by using programs like SIMQKE. In order to investigate the effects of this approach on wave propagation analysis it was decided to also include a set of artificial earthquakes that were generated using SIMQKE (Gasparini & Vanmarcke [8]) in a program version where some of the corrections suggested by Booth [9] were implemented.

In order to generate 'realistic' ground motions, the selection of a proper window function w(t) or 'Intensity function' I(t) - as it is called in the SIMQKE manual - is of crucial importance. In stochastic simulations of earthquake ground motion as in SIMUL and SIMQKE the window functions w(t) are used to shape band limited white noise to give it the transient character of real accelerograms. Boore [1] suggested the following form which was successfully applied by Kunze [6] for the simulation of Central European earthquakes:

$$w(t) = a\ t^b\ e^{-ct} H(t) \tag{5}$$

where

$$b = -\varepsilon \ln \eta / [1 + \varepsilon(\ln \varepsilon - 1)] \tag{6a}$$

$$c = b/(2\varepsilon T_d) \qquad\qquad a = \left[e/(2\varepsilon T_d)\right]^b \tag{6b}$$

H(t) is the unit step function and T_d is the strong motion duration. The constants η and ε were chosen to be 0.05 and 0.2 respectively. Based on the shape of the exponential intensity function of the program SIMQKE Lam [7] proposed the following window form:

$$w(t) = a_0 \left[\exp(-\alpha t / T_d) - \exp(-\beta t / T_d)\right] \tag{7}$$

For the maximum amplitude of w(t) to equal unity, a_0 must be:

$$a_0 = x\left(\frac{\beta}{\alpha}\right)^{1+x} \qquad\qquad x = \frac{\alpha}{\beta - \alpha} \tag{8}$$

A comparison of the two window functions (5) and (7) revealed, that constants $\alpha = 2.4$ and $\beta = 3.2$ give a good match of both shapes. The strong motion duration T_d can be determined using the relationship:

$$T_d = \frac{1}{f_c} + b\,R \tag{9}$$

where f_c is the corner frequency, R[km] is the hypocentral distance, and b is a constant (= 0.05) or a trilinear function of R (Atkinson & Boore [10]). Applying the focal parameters of the Roermond earthquake an approximate strong motion duration of $T_d \approx 3$ sec was derived and used together with the window function (7) and the rock spectra (soil class A1) of the E-DIN 4149 to generate 10 artificial earthquakes with SIMQKE. The mean (50% fractile) acceleration response spectrum of the generated time series is shown in Figure 2 and an example time history in Figure 3.

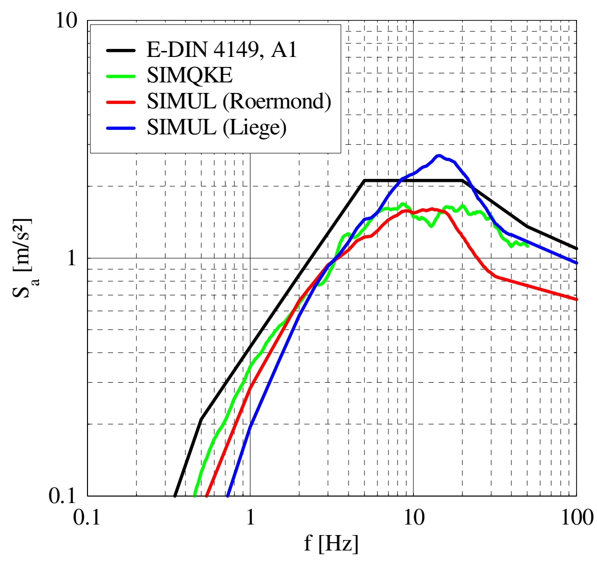

Fig. 2: Acceleration response spectra (50 % - fractile) at the free surface of the Devonian bedrock

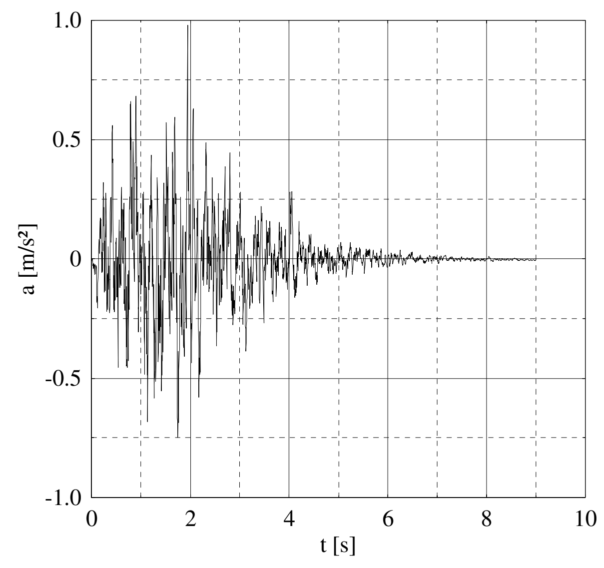

Fig. 3: Typical artificial earthquake generated by SIMQKE

For all synthetic accelerograms (SIMUL and SIMQKE) the seismic energy E_s and moment M_0 were cross-checked using the relationships:

$$E_s = \left(1 + \frac{1}{q}\right) \frac{\pi \rho R^2 v_s}{(R_{\theta\varphi})^2} \int \dot{u}^2(t)\, dt \tag{10}$$

where $R_{\theta\varphi}$ is the radiation pattern (assumption here: $R_{\theta\varphi} = 0.63$), $\dot{u}$ (t) the ground velocity and q is the ratio between S and P wave energy - following Boatwright & Fletcher [11] q = 20.
According to Kanamori & Anderson [12]:

$$M_0 \approx \frac{2 v_s^2 \rho}{\Delta\tau} E_s \approx 2 \cdot 10^4 E_s \tag{11}$$

The mean moment and seismic energy of the artificial earthquakes (SIMQKE) were about 25% higher than the values of the synthetic Roermond earthquakes (SIMUL).

MODELLING OF WAVE PROPAGATION IN THE SEDIMENT LAYERS

Three well known methods for the wave propagation analysis were used:
The first, the most simple was the analytical solution for a visco–elastic 2-layer system (Murphy [2]):

$$|T(\omega)| = \frac{2}{|\cos(k_1 d) + i\gamma \sin(k_1 d)|} \tag{12}$$

$$k_i^2 = \frac{\rho_i \omega^2}{G_i + i\omega\xi_i} \qquad \gamma = \frac{k_1(G_1 + i\omega\xi_1)}{k_2(G_2 + i\omega\xi_2)} \tag{13}$$

where G is the shear modulus, ξ the viscosity coefficient and k is the wave number. The solution was programmed and the recursive digital filter algorithm of Chronin [13] was added to calculate the response spectra.
The second, implemented in the program SHAKE 91 (Schnabel [14]); allows for the simulation of vertical shear wave propagation in horizontal soil layers. Both, linear and non-linear analyses were performed in order to investigate the influence of non-linear soil behavior. The non – linearity refers to the dependence of the shear modulus G and damping ratio D on the shear strain γ (e.g. Seed [15]).
The third method, implemented in the program SIMUL, is HASKELL's matrix algorithm (Haskell [16], [17]). It allows for the modeling of 2-dimensional wave propagation in horizontally layered soil with constant soil parameters. Attenuation due to material damping is introduced by complex wave numbers and all focal and soil parameters can be varied internally in a Gauss distributed manner.
As an input of externally generated acceleration time histories into SIMUL is not possible it was decided to model the standard earthquake events with SIMUL, whereas the wave propagation of the artificial earthquakes generated with SIMQKE was investigated using SHAKE 91 and the 2-layermodel.
To each of the proposed subregions for the Cologne area a uniform soil profile with the geophysical parameters shear wave velocity v_s, density ρ and quality factor $Q_s \approx 1/2D$ (D being the damping ratio) was assigned. The geophysical parameters were taken from Schön [18] and Budny [19]. The latter published as a result of a series of down–hole–measurements in 36 boreholes in the southern Lower–Rhine embayment the following relations between depth z vs. shear wave velocity and vs. quality factor:

$$v_s = 188 \cdot z^{0.21} \qquad\qquad Q_s = 2.66 \cdot z^{0.361} \qquad (14)$$

Taking additional publications (Brüstle [20], Steinmueller [21]) into account the following soil model for the Cologne area was derived:

Table 1: Geophysical soil model for the Cologne area (Germany)

Layer No.	Depth z [m]	Thickness h	v_s [m/s]	ρ [kg/m³]	Q_s
1	10	10	250	1900	10
2	20	10	330	2000	10
3	40	20	380	2000	20
4	60	20	430	2100	20
5	85	25	460	2100	20
6	120	35	500	2100	30
7	165	45	530	2200	30
8	220	55	570	2200	30
9	295	75	600	2300	40
10	390	95	640	2300	40
11	Devonian rock	1000	2500	2600	170
12	halfspace	-	3300	2700	200

The model of Table 1 was used for the calculations with SIMUL and SHAKE 91, whereby the γ vs. D and γ vs. G/G_{max} curves for the non – linear analyses with SHAKE were taken from Seed [15]. For the 2-layer model average soil parameters for the entire sedimentary cover were adopted.

RESULTS AND DISCUSSION

Figures 4 and 5 depict the transfer functions of the sediments and the response spectra (5 % damping) of the resultant ground acceleration at the free surface of two subregions. Comparing the 3 methods for wave propagation analysis one can conclude that:

1. All methods give good estimates of the first resonance frequency of the sedimentary cover. For all investigated subregions a good agreement between the numerically determined first resonance frequencies with the in-situ measured ground frequencies of Parolai [3] could be observed (Fig. 1), indicating the appropriateness of the chosen soil model (Table 1) and proposed zonation.
2. Clear differences can however be observed for the higher resonance frequencies in the transfer functions. Comparing the transfer functions of the linear and the non-linear SHAKE analyses, the typical shift of the resonance frequencies towards lower values for the non-linear case can be observed, which has to be attributed to the decrease of the shear modulus G.
3. Even larger differences are visible between the multi – layer models and the 2-layer model. Here the entire level of the transfer functions of the former models beyond the first resonance frequency is raised compared to the 2-layer model. The higher the number of layers the more pronounced is this feature. This fact is also reflected by a higher level of the corresponding response spectra.

4. Non-linear effects of the soil behaviour play - because of the rather small earthquake events and the accordingly small deformations - only a minor role. Only for shallow sediments some deviations from the linear spectra are visible.

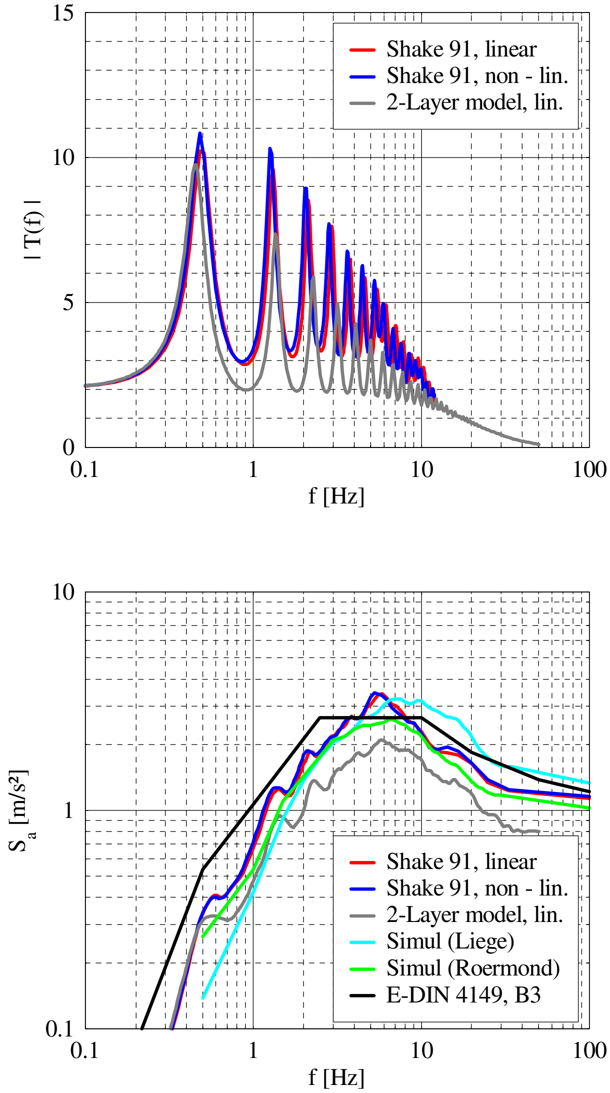

Fig. 4: Transfer function and response spectra, sediment thickness d = 295 m

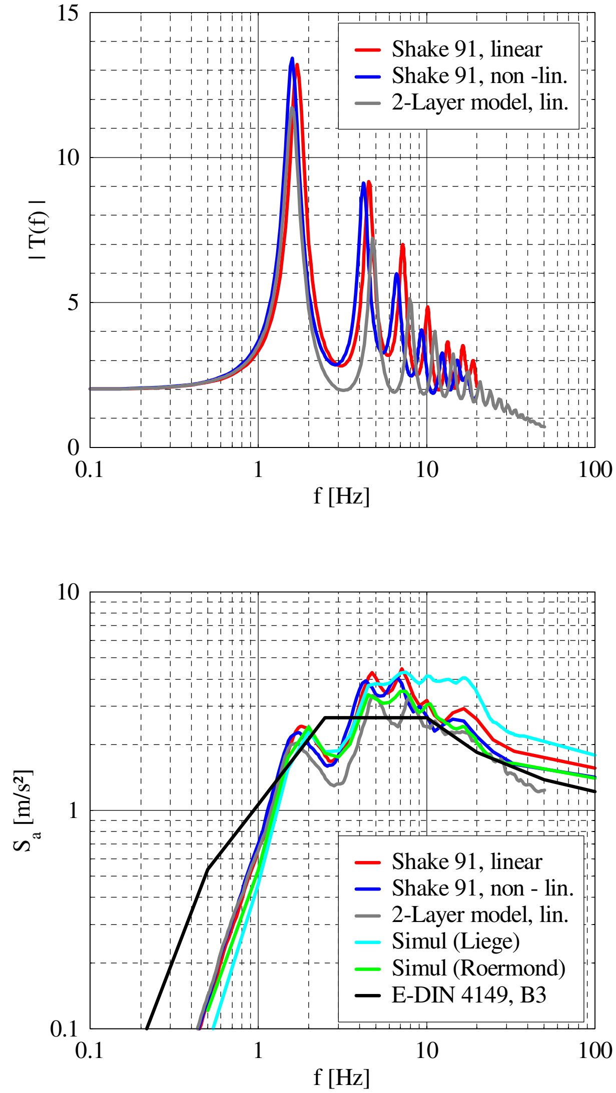

Fig. 5: Transfer function and response spectra, sediment thickness d = 60 m

According to the E-DIN 4149 the Cologne area can be assigned to the soil class B3, which is described by Brüstle [20] as:
Class B: Soft sediments (mainly Quaternary) with thickness up to 100 m; Tertiary sediments with thickness up to 500 m (with thin or without Quaternary coverage). Shear wave velocities increasing up to 1800 m/s in the Tertiary sequence and in the bedrock varying between 2000 and 3000 m/s.

The elastic acceleration response spectrum of the E-DIN 4149 has been added to Figures 4 and 5 to allow for comparison with the numerically determined response spectra. The following observations can be made:

1. For the soil model of Table 1 the response spectrum of the E-DIN represents well the spectra of the synthetic earthquakes for those subregions where the thickness of the sediments is between 400 and 100 m
2. For sedimentary covers thinner than 200 m the spectra of shallow events (e.g. Liege earthquake) exceed the E-DIN spectrum in the higher frequency region. Here the influence of the reduced attenuation of high frequency components in shallower sediments becomes visible.
3. For a thickness of the sediments smaller than 100 m the spectra of all events shift towards higher frequencies and exceed the E-DIN spectrum.

In order to account for possible deviations of the in-situ soil parameters from those in Table 1 parameter studies were performed. Therefore an input option of the program SIMUL was used that allows for the definition of uniform or Gaussian distributed parameters. Taking the standard event "Roermond" and the soil model of subregion 1 (Table 1) the influences of a uniform and a Gaussian distribution of the following parameters were investigated (Table 2). The values of the standard deviation and the limits of the uniformly distributed parameters were chosen to reflect the scope of the parameters in reality and to reflect the accuracy of the geophysical measurements in-situ. The measurement of the quality factor is thus the most uncertain.

Table 2: Parameter variations

Parameter	Stat. Expectation E[x]	Limits of the uniform probability density	Standard deviation σ[x] of Gaussian prob. density
Layer thickness h [m]	see Table 2	$0,85 \leq h/E[h] \leq 1,0$	$\sigma = 0,15\ E[h]$
v_s [m / s]	see Table 2	$0,90 \leq v_s/E[v_s] \leq 1,10$	$\sigma = 0,10\ E[v_s]$
ρ [kg / m³]	see Table 2	$0,95 \leq \rho/E[\rho] \leq 1,05$	$\sigma = 0,05\ E[\rho]$
Q_s [dl]	see Table 2	$0,70 \leq Q_s/E[Q_s] \leq 1,30$	$\sigma = 0,30\ E[Q_s]$

The evaluation of the results shows that the distribution of the layer thickness h, the shear wave velocity v_s and the density ρ have only a minor influence on the form of the mean response spectra – the calculated spectra are at some frequencies up the 10% lower than the spectra with constant parameters but usually fluctuate closely about the latter. The variation of the quality factor Q_s however shows an interesting peculiarity (Figure 6): For both forms of the probability densities are the spectral values beyond 3 Hz about 10 % to 20 % lower than the values with constant Q_s.

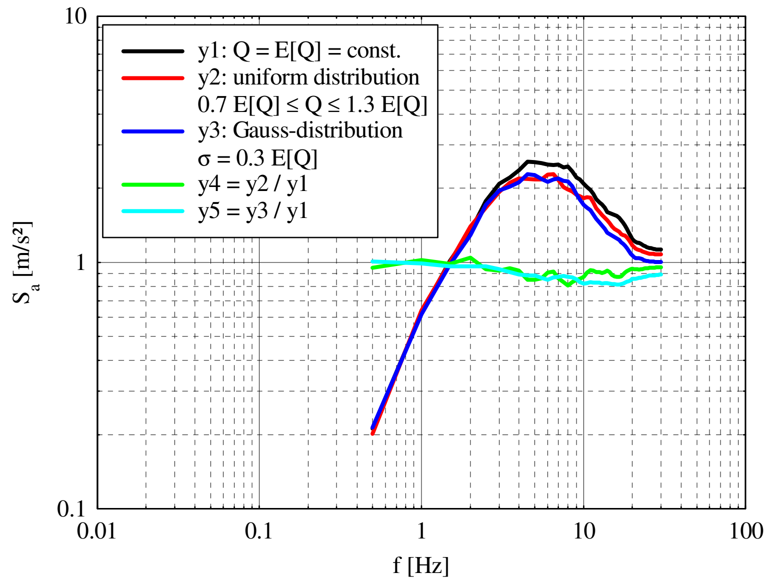

Figure 6: Response spectra for varying parameter Q_s

The mathematical reasons for this observation were investigated and the following was found:
The amplitude attenuation u_2/u_1 of a sinusoidal wave due to material damping can be described by the frequency dependent absorption coefficient $\alpha(Q, f)$:

$$g(Q,f) = u_2 / u_1 = Exp[-\alpha(Q,f)R] \qquad \alpha(Q,f) = \pi f /(Q v_S) \quad (15)$$

u_1 and u_2 being the wave amplitudes at the observation points 1 and 2 which are distance R apart from each other. $Q = Q_s$ and v_s are the quality factor and the shear wave velocity of medium in which the wave propagates. Assuming a uniform distribution of the variable Q about the mean value m = E[Q] within the limits Q_{min}= (1-n) m and Q_{max}= (1+n) m the following probability density function p(Q) and statistical expectation E[g(Q,f)] can be obtained:

$$p(Q) = 1/(2nm) \quad | \quad (1-n)m \le Q \le (1+n)m \qquad (16)$$

$$E[g(Q,f)] = \int_{-\infty}^{\infty} g(Q,f) \cdot p(Q)\, dQ = \frac{1}{2nm} \int_{(1-n)m}^{(1+n)m} Exp\left[-\frac{c}{Q}\right] dQ \qquad (17)$$

$$\text{with } c = c(f) = \pi f R / v_S$$

The solution of the integral on the right side of equation (17) in normalized form can be derived as:

$$\frac{E[g(Q,f)]}{e^{-c/m}} = \frac{1+n}{2n} e^{\frac{cn}{m(n+1)}} - \frac{1-n}{2n} e^{\frac{cn}{m(n-1)}} + \frac{c\, e^{c/m}}{2nm} \left\{ E_1\left(\frac{c}{(1-n)m}\right) - E_1\left(\frac{c}{(1+n)m}\right) \right\} \quad (18)$$

The term E_1 is the exponential integral of first order. For the 2-layer model of subregion 1 (R = 390 m, v_s = 569 m/s) and a mean value of m = E[Q] = 30. Figure 7 shows the dependence of the normalized expectation of g(Q, f) on the parameter n and the frequency f. In the frequency interval between 0 Hz and 20 Hz – the most important to civil engineers – a clear decrease of the mean values of the absorption term

(15) with uniformly distributed Q in comparison to the values with constant Q can be observed. This effect, which in a similar form can also be observed for a Gauss – distributed Q, is believed by the authors to be the reason for the above mentioned decrease of the spectral values when determined with statistically varying Q_s.

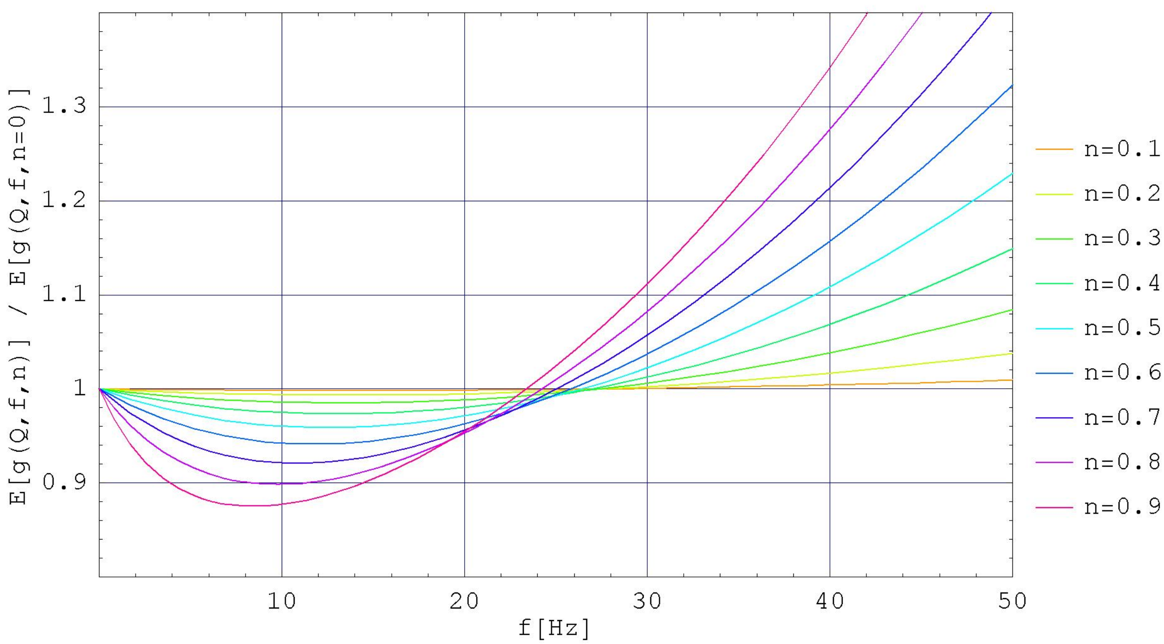

Figure 7: Ratio of the mean values of the absorption term (15) with uniformly distributed Q (n ≠ 0) and constant Q (n = 0)

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REFERENCES

1. Boore DA. "Stochastic simulation of high – frequency ground motion based on seismological models of the radiated spectra". Bull. Seis. Soc. Am. 1983; 73: 1865-1894.
2. Murphy JR, Davis AH, Weaver NL. "Amplification of seismic body waves by low-velocity surface layers". Bull. Seis. Soc. Am. 1971; 61 (1): 109-145.
3. Parolai S, Bormann P, Milkereit C. "Assessment of the natural frequency of the sedimentary cover in the cologne area (Germany) using noise measurements". Journ. Earthq. Eng. 2001; 5 (4): 541-564.
4. Schneider G. "Neue Bemessungsspektren für Deutschland". Referatensammlung, Gemeinschaftstagung Eurocode 8 / DIN 4149, Leinfelden-Echterdingen, 1998.
5. Langer H. „Seismotektonische Herdparameter und Ausbreitungseffekte bei Mikroerdbeben im Bereich der westlichen Schwäbischen Alb". Stuttgart: Berichte des Institutes für Geophysik der Universität, Nr. 2, 1986.
6. Kunze T, Langer H, Scherbaum F, Schneider G. „Site dependend strong ground motion simulation". Vogel A, Brabbes K. Editors. Earthquake Prognostics, Braunschweig, Wiesbaden: Vieweg & Sohn, 1986: 157-177.

7. Lam N, Wilson J, Hutchinson G. “Generation of synthetic earthquake accelerograms using seismological modelling: a review”. Journ. Earthq. Eng. 2000; 4 (3): 321-354.
8. Gasparini DA, Vanmarcke EH. “Simulated earthquake motions compatible with prescribed response spectra”. Mass. Inst. Techn., Dept. Civil Eng., Publ. No. R76-4, Order No. 527, 1976.
9. Booth E.: http://www.booth-seismic.co.uk/simqke_errors.htm, Edmund@booth-seismic.co.uk.
10. Atkinson GM., Boore DM. “Ground motion relations for Eastern North America”. Bull. Seis. Soc. Am. 1995; 85 (1): 17-30.
11. Boatwright J, Fletcher JB. “The partition of radiated energy between P and S waves”. Bull. Seis. Soc. Am. 1984; 74: 361-376.
12. Kanamori H, Anderson DL. “Theoretical basis of some empirical relations in seismology”. Bull. Seis. Soc. Am. 1975; 65 (5): 1073-1095.
13. Chronin DL. “Numerical integration of uncoupled equations of motion using recursive digital filtering”. Intern. Jour. Num. Meth. Eng. 1973; 6: 137-152.
14. Schnabel PB, Lysmer J, Seed HB. “User`s manual for SHAKE”. College of Engineering, Berkeley, California: Report No. EERC 72-12, 1972.
15. Seed HB, Wong RT, Idriss IM, Tokimatsu K. “Moduli and damping factors for dynamic analysis of cohesionless soils”. ASCE J. Geot. Eng. 1986; 112 (11): 1016-1032.
16. Haskell NA. “The dispersion of surface waves in layered media”. Bull. Seis. Soc. Am. 1953; 43: 17-34.
17. Haskell NA. “Crustal reflection of plane SH – waves”. Journ. Geoph. Res. 1960; 65 (12): 4147-4150.
18. Schön J. “Petrophysik“. Stuttgart: Ferdinand Enke Verlag, 1983.
19. Budny M. “Seismische Bestimmung der bodendynamischen Kennwerte von oberflächennahen Schichten in Erdbebengebieten der Niederrheinischen Bucht und ihre ingenieurseismologische Anwendung“. Sonderveröffentlichung Nr. 57 des Geologischen Institutes der Universität zu Köln, 1984.
20. Brüstle W, Geyer M, Schmücking B. “Karte der geologischen Untergrundklassen für DIN 4149 (neu) – Abschlußbericht“. LGRB Baden – Württemberg, Freiburg i. B., Az:2124.01/99-4764, 2000.
21. Steinmueller B. “Seismische Übertragungsfunktionen für typische Sedimentfolgen in Baden-Württemberg“. Ber. Inst. f. Geophysik, 3, Stuttgart, 1987.