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DEVELOPMENT OF INTENSITY COMPATIBLE TIME-HISTORIES FOR DYNAMIC ANALYSIS OF BUILDINGS

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Abstract

The functionality of critical infrastructures frequently depends on the availability of external support functions. Nuclear power plants are a typical example for such critical infrastructures as has been shown by the Fukushima accident. The loss of offsite power (failure of external infrastructures) caused by the earthquake triggered the accident by requesting a long term operation of emergency power supply systems that subsequently failed due to the additional tsunami impact. Therefore a realistic estimate of the damaging impact of earthquakes is crucial for preparing mitigative measures for disaster prevention and the analyses have to encompass not only the critical infrastructure itself but also external infrastructures that are necessary for safe long term operation in an emergency.

The only seismological parameter that implicitly contains all required information on the damaging impact of earthquakes is intensity. Additionally, intensity information directly captures spatial variation of ground motions related to the same or similar degree damage by construction of isoseismal lines. Therefore intensities are very suitable for predicting possible impacts of earthquakes on critical infrastructures including supporting infrastructures in closed proximity that are required for their functionality. For engineering applications intensity relevant information has to be converted into engineering characteristics. Because dynamic analyses (time-history analysis, frequently even non-linear ones) became a standard approach for the design and for the validation of safety of critical infrastructures it is reasonable to develop intensity compatible time-histories for engineering application.

In the paper the feasibility of a damage consistent performance-based seismic design of structures, systems and components is demonstrated. For this purpose a set of intensity compatible time-histories covering the intensity range between intensity VI and VII (EMS-98 scale) from a database of recorded time-histories is developed. These time-histories were used for the dynamic analysis of structures to develop in-structure floor response spectra. The results are compared with similar analysis results obtained by using time-histories derived from spectral matching of a uniform hazard spectrum from a large scale PSHA (PEGASOS). For the PEGASOS study the site intensity corresponding to the hazard background is known from hazard disaggregation. The comparison performed demonstrates that the use of traditional response spectrum analysis methods for the evaluation of the consequences of seismic hazard estimates derived from a PSHA in countries with low to moderate seismicity leads to conservative results. This is caused inherently by the PSHA-method. The computation of a uniform hazard spectrum (UHS) is based on the summation of exceedances probabilities of ground motion levels independently from the real damaging effects of the underlying earthquake. For a realistic assessment of the consequences of hazard estimates from a PSHA it is recommended to move towards a non-linear analysis of structures.

Keywords: seismic intensity; in-structure floor response spectra; dynamic analysis of structures; PSHA, uniform hazard spectrum

1. Introduction

Civil engineering standards for residential buildings in many countries are based on (frequently probabilistic – PSHA (Probabilistic Seismic Hazard Analysis)) seismic hazard assessments using ground motion parameters like peak ground accelerations and/or the associated response spectra (in case of a PSHA – uniform hazard spectra (UHS) as input hazard parameters. Experience has shown that the design of buildings to the maximum forces resulting even from low magnitude earthquakes is not economic. Therefore, load reduction factors (response factors) are applied in many civil engineering codes considering the performance of specific structure types during an earthquake. Thus, civil engineering codes permit for a limited inelastic response of structures in dependence on the required functionality (required performance) of the structure [1], [2]. For critical infrastructures like nuclear power plants several different levels of performance are considered. The underlying assumption is that the maximum ground motion level which is defined as an input for the design process is a measure of potential damage of earthquakes. This approximation may work reasonably well for large magnitude events (M>=7), while it is questionable for smaller earthquakes. The latter may cause high ground motion accelerations but their damaging effects are low or moderate. In case of a PSHA even the spectral shape of the UHS may coincide with the spectral shape of an UHS from another region there the hazard is driven by large earthquakes. Some engineering methods take this difference into account by incorporating additional load reduction (or, in case of a review of an existing structure, an additional safety) factor [3].

In general, ground motion accelerations and response spectra are poorly correlated with structural damage. The only single seismological parameter that is closely linked to damage as empirically observed is seismic intensity (e.g. in EMS-98 scale, [4]). Fig. 1 shows that completely different response spectra and similarly, completely different ground motion time-histories may cause the same level of intensity and therefore the same or a very similar level of damage.

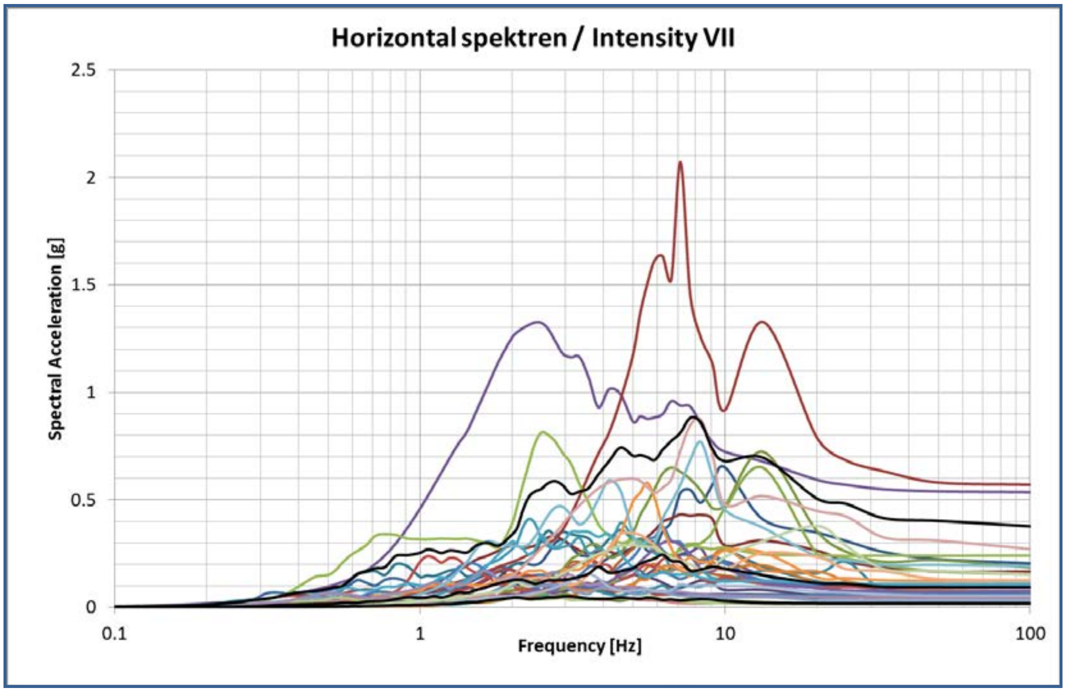

Fig. 1 – Horizontal ground motion spectra corresponding to site intensity 7 (for illustration)

Additionally for single source –single station variability, Fig. 2 shows horizontal ground motion spectra of Umbria Marche, Italy Earthquakes (3 different earthquakes in 1997) recorded by Station Cascia and Station Forca Canapina.

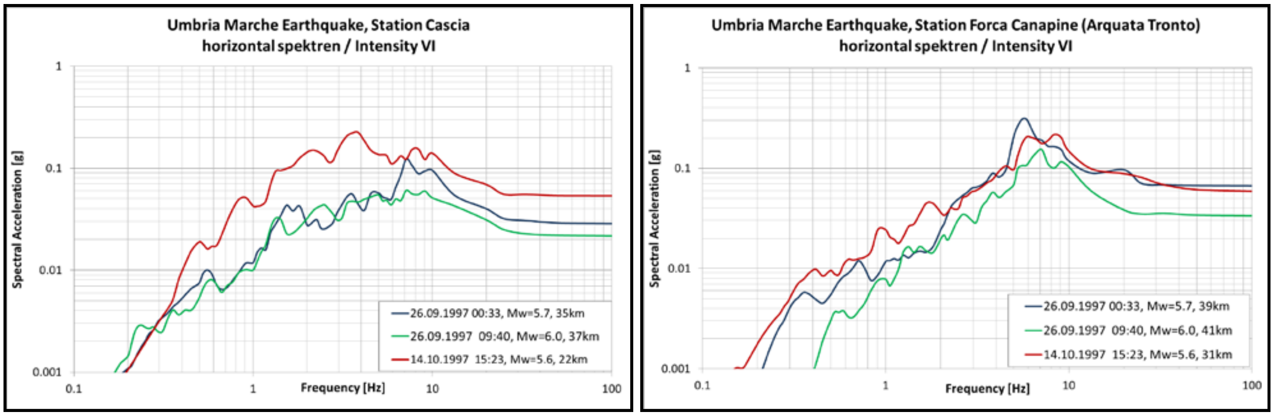

Fig. 2 – Horizontal ground motion spectra from single source- single site records

Neglecting the observed variability may lead to a systematic bias in performance - based design of structures. Therefore, the feasibility of a damage consistent performance-based design is investigated. To achieve this objective it is necessary to design structures, systems and components against a target site intensity level. The intension of this paper is to demonstrate the general feasibility of this design approach.

2. Methodology

A general requirement for an intensity compatible (and therefore damage consistent) design is that the seismic hazard analysis shall provide as a result the intensity level against which a structure shall be designed. For critical infrastructures like for example nuclear power plants it is also possible to define a mandatory minimum design level against earthquakes in terms of intensity for which the plant shall be designed (for example Intensity VII (EMS-98 scale [4])). Currently, IAEA defined the minimum design level in terms of PGA (0.1g).

The next step in the procedure consists in the conversion of intensities into engineering parameters. In general the following different methods can be applied to achieve this goal:

- Development and use of empirical conversion formulae (traditional approach),
- Calibrated modeling approach, e.g. development of source-, path- and site compatible synthetic seismograms that are calibrated against the specified intensity level [5]
- Direct use of intensity compatible time-histories from recorded earthquakes.

In the analyses presented here the last method was applied. For this purpose the “Resorce database” [6] was reviewed that contains more than 4’000, 3-component (X, Y, Z) time-histories from recorded earthquakes in Europe, Turkey and Iran was reviewed. For each of the recorded earthquakes the epicentral intensity, the site intensity factor and the site intensity were calculated. For this purpose the following equations were used:

Epicentral Intensity:

$$I_0\left(M_W\right)=33.631-\sqrt{1120.8-79.365M_w}\text{, for shallow earthquakes} \tag{1}$$

Site Intensity (Factor):

$$\begin{aligned} &I=I_0-3\log\left(\frac{R}{h}\right)-1.3\alpha\left(R-h\right)\text{; for shallow earthquakes} \\ &h\approx 7km,\ \alpha=0.002 \end{aligned} \tag{2}$$

In Eq. (1) and Eq. (2) h represents the hypocenter depth, M_w the moment magnitude, R the hypocentral distance, and α an attenuation factor. Because this process inherently includes some calculation uncertainty the calculated site intensity factors (decadal system) were rounded to the next integer value to obtain the site intensity. Eq. (1) was developed by orthogonal Chi-square regression [7], [8], following the approach described in [9]. For the development of the equation a combination of earthquake catalogs was used including two German catalogs (Grünthal and Wahlström, Leydecker) [10], [11] and the earthquake catalog of Switzerland (ECOS (2002)) [12] used in the PEGASOS-Project. The three catalogs were merged into a site-specific catalog for the NPP Goesgen site [8]. This work was a part of the review of the results of the PEGASOS project [13]. Fig. 3 shows horizontal ground motion spectra corresponding to different values of site intensity.

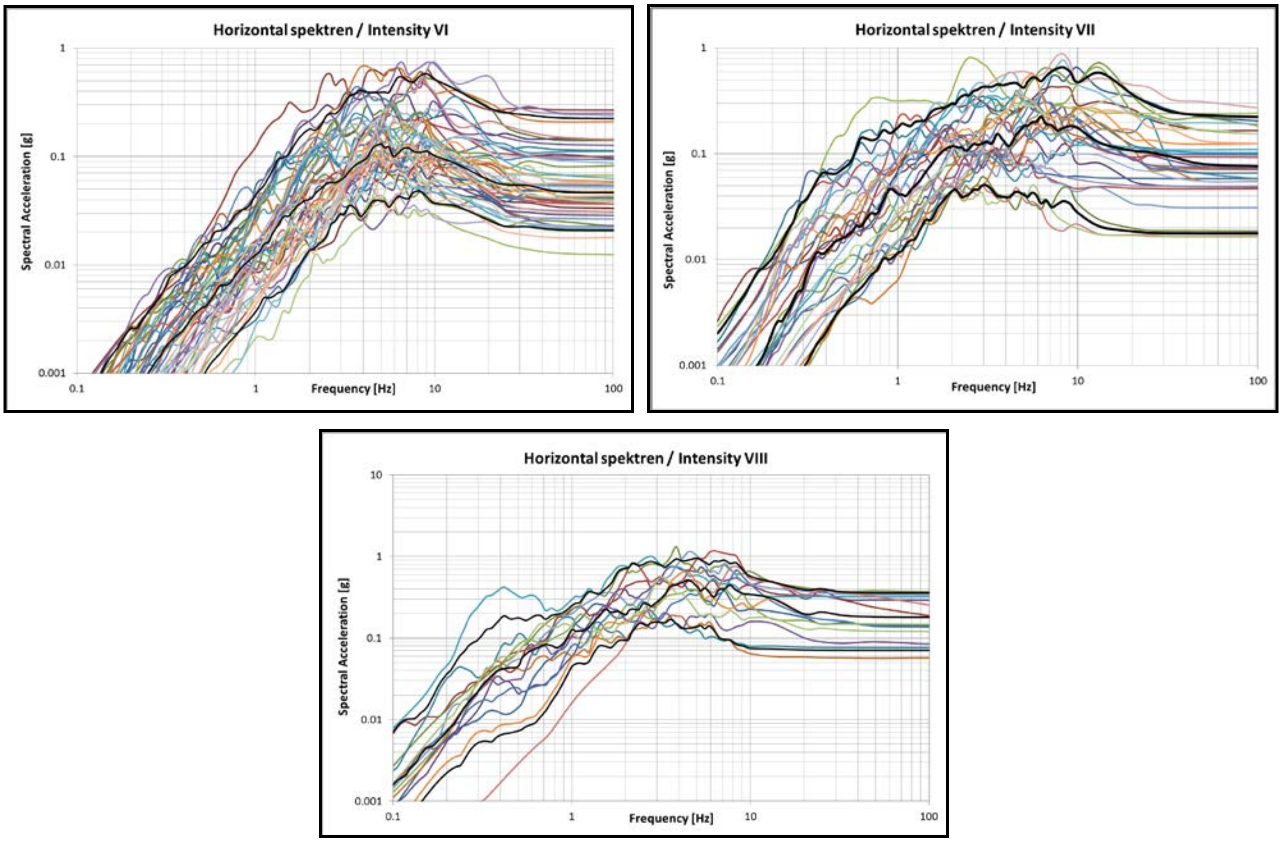

Fig. 3 – Horizontal ground motion spectra corresponding to site intensity VI, VII and VIII

3. Structural Analysis

Subsequently all recorded earthquake time-histories were classified into the corresponding site intensity. For each of the intensity catagories a set of time-histories was selected and used for the calculation of in-structure floor response spectra of the reactor building of NPP Goesgen-Daeniken. For the analysis a 3D-model and the soil-structure interaction code SASSI2010 were used. Fig. 4 shows the model of the reactor building used for the analysis.

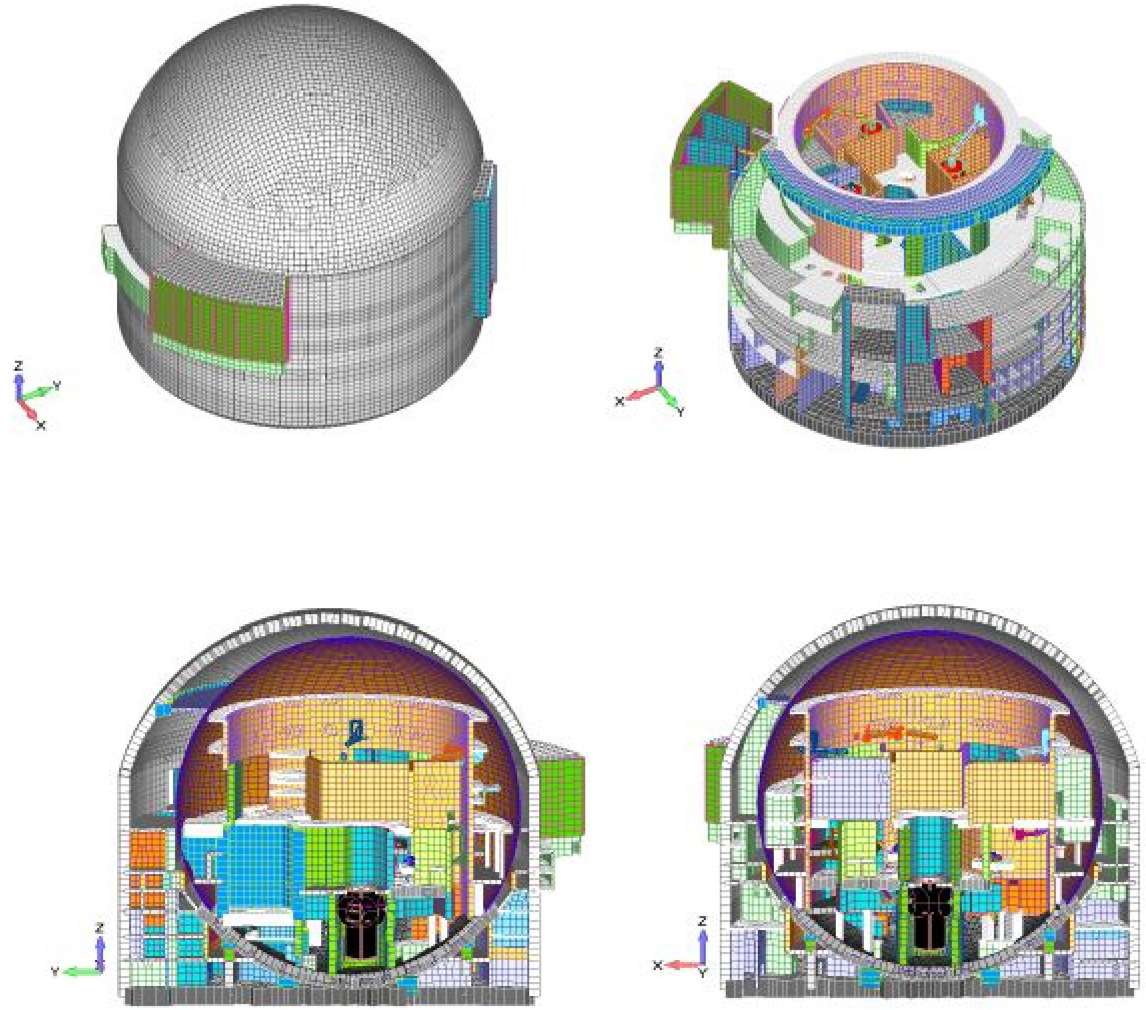

Fig. 4 – 3D FE Model of the reactor building

The approach taken ensures the direct incorporation of response spectra and time-histories varaibility into the structural analysis.

For comparison a similar analysis was performed by using the results from the PEGASOS project for NPP Goesgen-Daeniken. According to design criteria in Switzerland the mean UHS for a frequency of exceedance of

10^{-4}/a had to be applied. From the disaggreation of the hazard into controlling earthquakes [14], it is known that the mean value of site intensity factor corresponding to the bivariate distribution of controlling earthquakes (in terms of pairs of magnitude and distance) for the Goesgen site is VII.5. Therefore, it makes sense to compare the in-structure floor response spectra for intensity levels VII and VIII with the corresponding spectra from the PEGASOS study (for a frequency of exceedance of 10^{-4}/a). The comparison allows to judge the degree of conservatism inherently embedded into the PSHA spectra in comparison to response spectra corresponding to the site intensity level of the hazard background.

Fig. 5 shows typical time-histories selected for the structural analysis. The review of time-histories once again demonstrated that completely different time-histories may lead to the same or a similar degree of damage within the accuracy of the intensity scale.

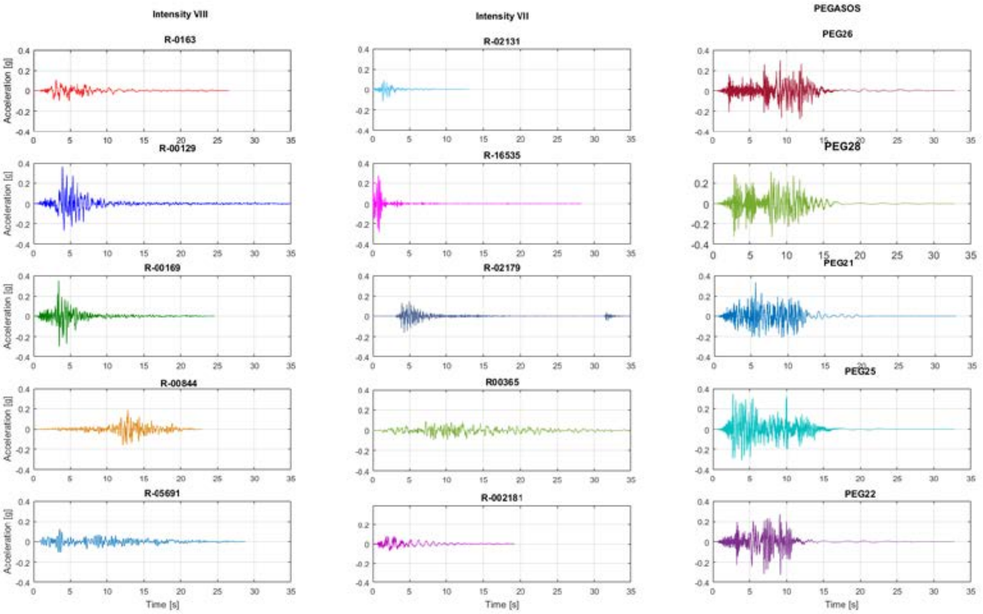

Fig. 5 – Time-histories for the structural analysis (from left to right, intensity VIII, intensity VII, and PEGASOS-UHS (10-4/a)- shall correspond to intensity VII.5

4. Results of the Analysis

The in-structure floor response spectra were evaluated and compared for two nodes at two different elevations (5m level – equipment floor, and spent fuel pool floor -18m level). The comparison of the intensity compatible in-structure floor response spectra with the PEGASOS spectra (UHS for a frequency of exceedances of 10^{-4}/a) is shown in Fig. 6 and Fig. 7.

The figures also illustrate that the variability of time-histories associated with different earthquakes belonging to the same intensity category is captured in the analysis. By making the usual assumption that each of the time-histories within an intensity category has an equal weight (assumption about uniform distribution) it is possible to establish performance objectives for the design of structures, systems and components. For example, it can be required that a structure or a component withstands earthquakes of a certain intensity level with 95% or 99% confidence. Because intensities in EMS-98 scale can also be associated with different damage grades it is also possible to define performance goals in the sense that the damage grade of a structure with a specified confidence level shall not exceed a certain level (e.g. insignificant damage for intensity VII, moderate damage for intensity VIII)

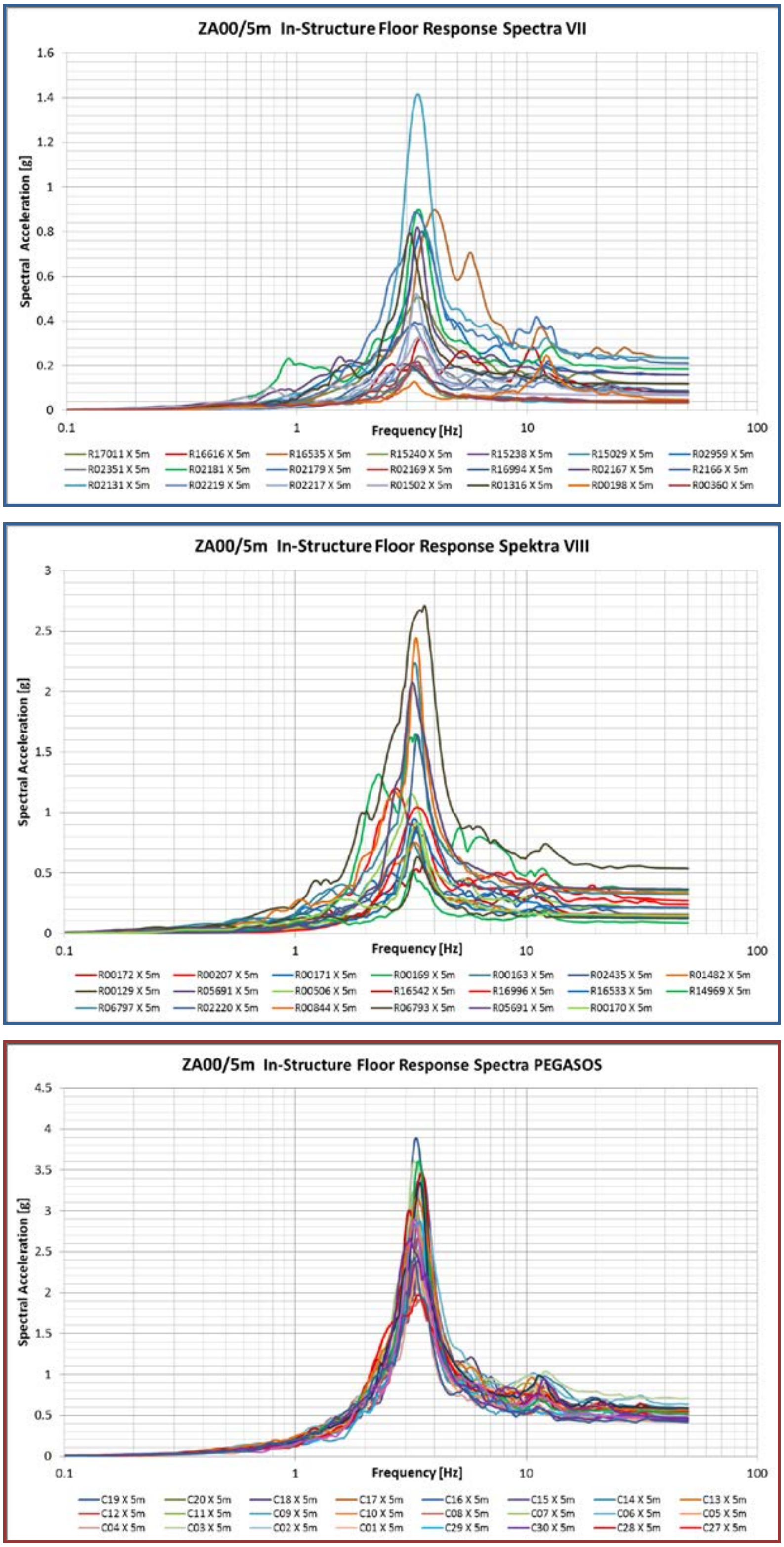

Fig. 6 - Comparison of in-structure floor response spectra, reactor building, elevation 5m

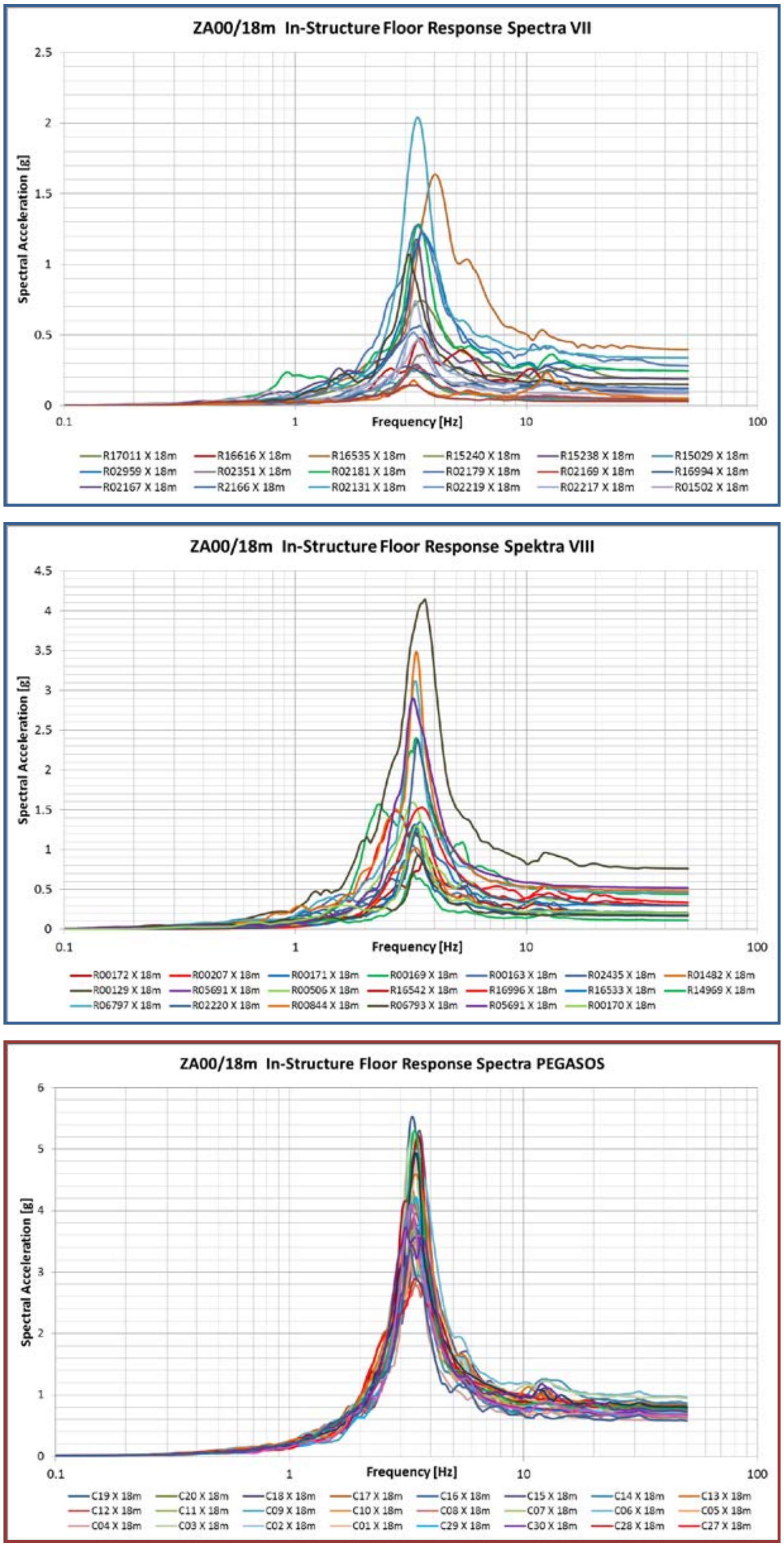

Fig. 7 - Comparison of in-structure floor response spectra, reactor building, elevation 18m

The in-structure floor response spectra derived from the PEGASOS -study (UHS for 10^{-4}/a) significantly exceed the comparable intensity VIII spectra despite the fact that the controlling PEGASOS earthquakes can cause only a damage corresponding to an intensity level of VII.5 (intensity factor). Therefore, an evaluation of the consequences of hazard assessment results using traditional response spectra (force-based) methods may lead to overly conservative results. It is important to remember that the process of damaging a structure is a non-linear process for which it is necessary to perform destruction work. To perform work energy is required. This energy is only available in form of the seismic input energy of the earthquake. Therefore a “weak” (non-damaging, low magnitude) earthquake remains to be a “weak” earthquake whatsoever its peak ground acceleration or response spectrum is.

On the other hand from a safety perspective one can conclude that the use of the traditional methods leads implicitly to the incorporation of an additional safety factor. In the case of the PEGASOS study this safety factor corresponds to one unit in intensity scale. This corresponds approximately to a factor of two in terms of PGA accelerations. This picture may change for high seismic regions where the hazard is dominated by large magnitude events. The reason is that lower but long lasting accelerations may cause significant damage that exceeds the usual force-based predictions.

The root cause of the artificial amplification of response spectra in PSHA-studies in areas of low to moderate seismicity has been established before [14]. The computation of a uniform hazard spectrum (UHS) is based on the summation of exceedances probabilities of ground motion levels independently from the real damaging effects of the underlying earthquake. Because in low seismic areas the hazard is controlled by small near-site earthquakes which have a relative high frequency of occurrence the UHS is amplified in terms of acceleration while the hazard background in intensity scale remains to be of low or moderate level. From the persepctive of damaging effects the UHS of a PSHA is not uniform.

To obtain a more realistic assessment of the consequences of the results of a site-specific PSA which takes into account all sources of uncertainty it is necessary to perform non-linear structural analysis. This is needed to capture the differences in the damaging effects of short and long duration earthquakes with different seismic input energy leading to the same site response spectrum [3], [14]. To perform such an anlysis the results output of PSHA has to be expanded, because for a realistic assessment the joint probability distribution for response spectra and strong motion duration (or the combination with another parameter characterizing the strong motion duration or input energy) is needed.

4. Conclusions

The general feasibility of a damage consistent performance-based design of structures, systems and components was demonstrated.

Additionally, it was confirmed that the summation of exceedances probabilities for specified acceleration levels as it is common in the current PSHA methodology [13] [15], and their combination into a UHS for low to moderate seismic areas leads to an artificial amplification of the hazard due to the inclusion of non-damaging earthquakes. For identifying these difference non-linear structural analysis is needed. For this purpose the output of a PSHA in form of a UHS is not sufficent. The joint probability distribution of acceleration response spectra and strong motion duration (or the combination with another parameter characterizing the strong motion duration or input energy) is needed to peform a realistic risk assessment and to avoid an overly consersative seismic design.

The current practice of using response spectra based methods for the analysis of the consequences of PSHA hazard estimates leads to an inherently embedded additional safety margin for low and moderate seismic areas. In seismically very active regions on contrary the evaluation of the consequences may be too optimistic.

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