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A STUDY ON SITE-SPECIFIC UNIFORM HAZARD RESPONSE SPECTRUM IN PROBABILITY SEISMIC HAZARD ANALYSIS

Y. W. Chang[1], W. Y. Jean[2], C. H. Loh[3] and J. F. Chai[4]

ABSTRACT

The uniform hazard response spectrum (UHRS) is determined based on the spectral accelerations corresponding to a given probability of exceedance in the probability seismic hazard curves. Generally, the seismic hazard curve for a specific site represents the relationship between occurrence frequencies considering various earthquake characteristics and spectral accelerations using an attenuation law for the hard site within a defined range around the site. The accuracy of the estimation for spectral accelerations at a specific site strongly depends on the geologic condition underlying the site. Therefore, the local site effect should be taken into account for a defensible seismic hazard analysis. In this study, the local site effect is considered using the site-specific attenuation law and local site amplification factor, that both are obtained from the earthquake database around the site, in probabilistic seismic hazard analysis. Through the aforementioned processes, the site-specific uniform hazard response spectrum corresponding to a given probability of exceedance can be determined. Finally, the damage earthquake data near the specific site are used to refine the uniform hazard response spectrum at several periods of the seismic characteristic of the site.

Introduction

On September 21, 1999 (Taiwan local time), a disastrous earthquake of magnitude M_L=7.3 struck the central part of Taiwan. The epicenter was located near the town of Chi-Chi, Nautou County. Along the Chelungpu fault, a surface rupture of more than 90 km was observed. A horizontal offset about 10 meters was observed at another site. As a direct lost of this earthquake, 2403 people were killed, over 10,000 buildings collapsed or were severely damaged (Loh and Lee 2000). This is Taiwan's worst disaster since the 1935 ShinChu-Taichung earthquake, where 3325 people were lost in a magnitude M_L=7.1 earthquake. The devastating earthquakes in Taiwan occurred mostly with ground ruptures or resulted entirely from the reactivation of faults. Earthquake hazard mitigation is an important issue in Taiwan. The activity

[1] Assistant Research, National Center for Research on Earthquake Engineering, Taipei, Taiwan
[2] Researcher, National Center for Research on Earthquake Engineering, Taipei, Taiwan
[3] Professor, Dept. of Civil Engineering, National Taiwan University, Taipei, Taiwan
[4] Researcher, National Center for Research on Earthquake Engineering, Taipei, Taiwan

of the faults must be determined to provide information for seismic hazard analysis and earthquake mitigation.

The principal objective of seismic hazard analysis is to estimate the likelihood that different levels of ground shaking intensity will be experienced at a site. The analysis must account for the spatial and temporal randomness of earthquake occurrences, and the uncertainty in ground motion predictions for events of different magnitudes at random distances. The methodologies for performing a probabilistic seismic hazard analysis (PSHA), as initial described by Cornell (1968), McGuire (1976), Der Kiureghian & Ang (1977), and others, are well established in engineering practice. Actually, it is worthy of noting that there are two major sources of probabilistic uncertainties in the probabilistic seismic hazard analysis (McGuire, 2004): (1) aleatory uncertainties that is inherent in a random phenomenon and cannot be reduced by acquiring additional data or information; and (2) epistemic uncertainties that results from lack of some model or parameter, also been called statistical uncertainties. In this paper, the general methodology of PSHA and the basis of inputs to the PSHA are summarized.

Although the characteristic earthquake model was adopted in the hazard analysis, the current seismic zonings of Taiwan's building code utilized time-independent estimates of recurrence rate of earthquakes (Youngs and Coppermith 1985; Loh and Huang 2002). The time-dependence of characteristic earthquake should be considered for some of the major faults that have semi-periodic behavior and for which sufficient information on previous earthquakes is available. To make the time varying probability calculations, one needs the information on the date a fault last ruptured, the mean inter-event time of large events, and its standard deviation. Based on the paleoseismology investigations conducted by the Central Geological Survey, Taiwan, the time-predictable characteristic earthquake model was adopted to evaluate the seismic hazard for the major active faults. Earthquake recurrence intervals for characteristic events from the active faults were analyzed and modeled by the lognormal probability distribution function (Chang et al. 2007). The time-predictable characteristic earthquakes model are used in the hazard analysis for the Type I active faults.

For site effect, the Taiwan Strong Motion Instrumentation Program (TSMIP), which operated by the Central Weather Bureau (CWB) for the populated areas with dense digital strong-motion networks, composed of more than 700 stations widely deployed in Taiwan area. On the other hand, in 2000, NCREE and CWB collaborated to perform the site investigation to obtain basic soil properties and wave velocity of the stratum. This geological database is a good reference for understanding the characteristic of seismic data. Accordingly, a large amount of the high quality earthquake data collected by the network of TSMIP can be used in this study to more deeply investigate the site amplification effect on the par in response to different levels of excitation.

Background Seismicity

Monitoring of regional seismicity in Taiwan has been significantly improved since 1990 after the CWB installed dense networks of strong motion accelerographs and real-time seismic stations with high-gain velocity sensors. The history of earthquake activity in the Taiwan region can be dated back to the seventeenth century. The sources of earthquake catalogue include historical records and instrumented earthquake data. To review historical seismicity, the catalog of pre-instrumented earthquakes had been compiled and modified by Cheng and Yeh (1989). This catalog provides a list of historical earthquakes dating back as early as 1604. Additional, due to the high seismic activities in Taiwan, the Central Weather Bureau (CWB) launched a seismic instrumentation program using digital strong-motion seismograph since 1990. Fig. 1 shows a map of earthquake epicenters in Taiwan area from 1900 to 2007. In the figure the size of dots represents magnitude, whereas the color represents focal depth (h): red for $h < 20$ km, green for $50>h>20$ km, and blue for $h>50$ km. It is apparently related to the subduction of the Philippine Sea plate under the Eurasian plate in northeastern Taiwan. There are significant earthquake activities under Taiwan Island due to collision of the two plates.

Analysis Model Parameters for PSHA

The PSHA provides a framework to address the uncertainties associated with the identification and characterization of seismic sources by incorporating multiple interpretations of seismological parameters. The role of geological, seismological, and geophysical investigations is to develop geosciences information about the site for the detailed design analysis of the facility, as well as to ensure that the seismic hazard analysis can include the up-to-date information. Besides, a logic tree approach was used to incorporate credible alternatives for seismic source interpretations, seismic source parameters, and ground motion attenuation models.

Earthquake catalog

In the last catalog, which collected earthquake data from 1900 to July 1989, was used to calculate the hazard for plant site in the previous PSHA study. In recent years, many efforts were performed to reexamine the source parameters (magnitude, epicenter, and focus depth) of the earthquake catalog by many researchers. Some double counted earthquakes were removed from last catalog, and, the earthquakes occurred in the last decade were added into the catalog.

The instrumentally determined earthquakes in Taiwan from 1898 to 2000 had been recompiled (Cheng et al., 2003). Earthquake magnitudes used in different period were reviewed, and the relationships among them were derived. According the empirical formula, the currently used local magnitude, M_L (Shin, 1993), was used as a uniform scale to describe the size of earthquake. Depending on the number of seismic station and the performance of seismograph, the history of earthquake observation was divided into 4 stages: initial stage (1898-1935); intermediate stage (1936-1972); TTSN stage (1973-1991.2), and CWBSN stage (1991.3-), to describe the quality of events. The data compiled in this catalog include the origin time, epicenter, focal depth, magnitude, information sources, and damaged earthquakes. Fig. 2 showed the occurrence time of earthquake events of magnitude greater than 5.0 for different instrumental period of the old catalog and the new one for selected sub-zones, BS02. It is noted that the earthquake catalog adopted by old catalog showed a large change in the occurrence rate for different instrumental period, especially, for the period from 1936 to 1973. The new compiled earthquake catalog, which is more reasonable then the old one, was used in this study.

Time-predictable characteristic earthquake model

The study work of paleoearthquakes investigation performed by Chen (Chen et al. 2004) showed that the rupture of the Type I active faults in Taiwan followed the occurrence-time-predictable earthquake model. Based on the paleoseismology investigations conducted by the Central Geological Survey, Taiwan, the time-predictable characteristic earthquake model was adopted to evaluate the seismic hazard for the major active faults. Earthquake recurrence intervals for characteristic events from the active faults were analyzed and modeled by the lognormal probability distribution function (Chang et al. 2007).

The 1999 Taiwan earthquake caused a clear surface rupture of more than 90 km along the Chelungpu fault. Seven trenches were excavated along this fault to investigate the history of large earthquake events. The excavations along the fault have characterized six large earthquake events in 1999 A.D., 300-430 cal yr B.P., 680-790 cal yr B.P., 710-950 cal yr B.P.,1380-1700 cal yr B.P., and 1710-1930 cal yr B.P. during the past 2 millennia (Chen et al. 2007; http://cgsweb.moeacgs.gov.tw/). The measured average recurrence interval for the Chichi earthquake through event E5 allows us to conclude that there were relatively short recurrence intervals of 415±65, 370±120, 95±175, 710±280, and 265±255 years. As shown in Fig. 3, the mean recurrence interval of characteristic earthquakes is about 364 years and the variance is small, the coefficient of variation (COV) is 0.37. This small COV value, which is similar to some other research result (Sykes and Menke 2006), suggests a regular recurrence interval of characteristic earthquakes for the Chelungpu fault. Therefore, the time-predictable earthquake model could describe the activities very well for the Chelungpu fault. Similarly, the Longitudinal Valley fault, which consists of many segments, is currently the major seismogenic fault in Taiwan. The Longitudinal Valley fault is also the most important plate boundary fault between the Philippine Sea plate and Eurasia continent in Taiwan. Through the investigation of three sites along the Longitudinal Valley fault, four reverse fault strands with three paleoearthquake ruptures occurred in A.D. 1951 and in the periods A.D. 1736-1898 and A.D. 1564-1680. The mean occurrence interval for the past 390 yr (1951-1564) is approximately 150 yr (Fig. 3)(Yen et al. 2008). Based on the empirical relationships of magnitude and surface displacement, the moment magnitudes of the paleoearthquakes were about 7.0-7.2.

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In these cases, the time-independent characteristic earthquake model is used in the hazard analysis. In other word, the constant rate Poisson process model is adopted to calculate the hazard contributed from these faults of limited information.

Site effect analysis

Based on the hard site attenuation relationships (Jean et al. 2006), site effects from the plant site are discussed in terms of a site-dependent bias function. From the instrumental stations of the TSMIP network near the plant site, a systematic bias caused by the seismic data scattering in the attenuation form was found. It is believed that the systematic bias mainly comes from the geological factor of the specific site characteristics and some other effects. It is necessary to reduce the data scattering in the attenuation forms by removing the systematic bias (Jean et al. 2006). For this purpose, a residual is defined as the difference between the observed and predicted values of the natural logarithm of PGA (or other ground motion parameters). Comparison on both the PGA between observed data and those calculated from the hard site attenuation relationships is made and shown in Fig. 4. There also shows the results of spectral response acceleration at short period of 0.3 sec(S_{as}) and long period of 1.0 sec(S_{a1}). For the case that the data points fall onto the dashed line indicated that the reference attenuation form can predict well for this site (no significant site effects and original attenuation form can be used). In Fig. 4, it shows that plant site has large amplification effect. Based on the calculated data from the hard site attenuation relationships, the site amplification factor for plant site can be developed by Eq(1)

$$\ln(Y_o) = C_0 + C_1 \cdot \ln(Y_r) \tag{1}$$

where Y_0 is observed data (either PGA or Sa-value), Y_r is the calculated data from the hard site attenuation form, and the coefficients C_0, C_1 were the site amplification factor for plant site (Fig.4), which were obtained by regression analysis using earthquake data. These parameters of site amplification factor will be used to estimate accurately intensity values for PSHA.

For plant site, the seismic data from TSMIP stations which are close to the plant site are used to develop a site-specific attenuation form. The seismic data from TSMIP stations in which the site condition are similar to the plant site were used to conduct the regression analysis to simulate the site characteristic of plant site. From the data set, it is found that the developed median site-specific attenuation form in this study could conservatively represent the site-specific ground motion for plant site, and this median attenuation form could be used in seismic hazard analysis in a very conservative manner.

Based on the uncertainty analysis of the site-specific amplification effects in response to different levels of excitation, there are two opinions to consider the site effect from the plant site:(1)The developed median site-specific attenuation relationships from this study could conservatively represent the ground motion for plant site and could be used in seismic hazard analysis in a very conservative manner; (2)The site amplification factor for plant site was calculated by using the same data set, as shown in Fig.4. The proposed hybrid procedure, which combines the hard site attenuation form and the site amplification factor, could estimate the site-specific ground motion hazard curves in SHA.

Uniform Hazard Response Spectrum (UHRS)

Seismic hazard curve

Before evaluating the final seismic hazard curves for plant site, much effort were put on conducting the sensitivity analyses of the seismic hazard parameters. A number of sensitivity studies were performed, each of which was aimed at examining and determining the effects of variations on the seismic hazard for a given set of models parameter. The model uncertainties as well as the parameter uncertainties were considered in the analysis to provide a set of distribution on the frequency of exceedance. The resulting distribution provides a quantitative assessment of the uncertainly in seismic hazard.

The finial set of seismic hazard curves were obtained using the logic-tree framework (Coppersmith and Youngs 1986). The nodes of logic-tree include zoning schemes, occurrence rate of earthquake, attenuation relationships and site effects of the plant site. In this study, the aforementioned eight hazard curves reflect the effects of all the uncertainties underlying the hazard calculation, including the dispersions in the attenuation equations. To find a single best-estimate seismic hazard curve, it is necessary to weight the eight hazard curves using the independent subjective judgments of experts in the project team. The final best estimate mean hazard curves (50%) of PGA as well as its 10~90 percent uncertainty band developed by this study are obtained and shown in Fig. 5.

Design Spectrum

For the purpose of establishing a uniform hazard response spectrum (UHRS) of PSHA based on the proposed spectral attenuation relationships, the annual frequency of exceedance of two specific periods was calculated. For the seismic design code for buildings in Taiwan, the elastic seismic demand is represented by the design spectral response acceleration S_{aD} corresponding to a uniform seismic hazard level of 10% and 2% probability of exceedance within 50 years which corresponding to 475-year and 2500-year return periods. Based on the seismic parameters, S_{DS} and S_{D1}, the 5%-damped simple uniform hazard response spectrum (UHRS) can be developed by Eq.(2)

$$S_{aD} = \begin{cases} S_{DS}\left(0.4+3T/T_0\right) & ; \quad T \le 0.2T_0 \quad (very \quad short \quad period) \\ S_{DS} & ; \quad 0.2T_0 < T \le T_0 \quad (short \quad period) \\ S_{D1}/T & ; \quad T_0 < T \le 2.5T_0 \,(medium \quad long\; period) \end{cases} \tag{2}$$

where S_{DS} and S_{D1} are spectral response acceleration at period of 0.3 sec and 1.0 sec, respectively. Corner period T_0 is a ratio of S_{D1} to S_{DS}. Following the Eq.(2), Fig. 6 shows the comparison on the uniform hazard response spectrum (UHRS) for plant site and the seismic parameters specified by the design code. The results imply that the parameters S_{D1} prescribed in the design code for general site may underestimate the seismic demand for plant site. Considering the proposed specific parameters in probabilistic hazard analysis the results could full describe the seismic characteristic of plant site.

TSMIP Database

In order to develop a site-specific design spectrum, the seismic characteristic of the observed records from the TSMIP stations which are closed to plant site will be used to modify the simple UHRS from PSHA. Based on the TSMIP network, the normalized 5%-damped horizontal response spectra (both NS and EW components) corresponding to the stiff condition of plant site are selected. Among the earthquake events occurred from 1991 to 2007, four earthquake events with the magnitude M_L greater than 5.5 were selected. From those four selected earthquake events, fourteen earthquake histories with PGA greater than 50gal recorded by three stations of the TSMIP network within and around plant site were adopted in the desired analysis database. The locations of the epicenters of those 4 selected earthquake events and the main shock of the 1999 Chi-Chi earthquake and 2006 Pingtung earthquake are also observed. Obviously, using the appropriate database for analysis is capable of determining a more adequate distribution of seismic characteristic for plant site.

In order to understand the dominant frequency of the ground motion of plant site, a total of fourteen 5%-damped horizontal response spectra were separated into three groups: 'PGA≥50gal', 'PGA≥80gal' and 'PGA≥100 gal'. Fig. 7 shows the comparison of the simple UHRS of 475 year return period for plant site. The results imply that the dominant period range of site characteristic is between 0.16 s and 0.4 s, and further, for other periods, the mean of 5%-damped horizontal response spectrum determined by TSMIP data for plant site can almost be enveloped by the design spectra proposed in PSHA.

Site-Specific Design Response Spectrum

The other objective of the project is to evaluate the validity of the design response spectrum that was developed for the plant site. From the results presented in Fig. 8, based on the averaged response spectra from the groups of response spectra of ″PGA≥50 gal″ and ″PGA≥80 gal″, respectively, an approach have been developed to generate the site-specific design spectrum for plant site. During the short-period, an envelope curve was developed to cover the site characteristic. In this case, the site-specific design response spectrum for plant site will be divided into four sections. The proposed design spectrum with two specified return period are shown in Fig.8:

for 475-year return period:

$$Sa(g) = \begin{cases} S_{DS}(0.4 + 0.3T/T_0), & T < 0.16 \\ 0.727, & 0.16 < T \le 0.4 \\ -0.2114T + 0.8116, & 0.4 < T < T_0 \\ S_{DL}/T, & T > T_0 \end{cases} \tag{3}$$

for 2500-year return period:

$$Sa(g) = \begin{cases} S_{DS}(0.4 + 0.3T/T_0), & T < 0.16 \\ 1.007, & 0.16 < T \le 0.4 \\ -0.2326T + 1.1, & 0.4 < T < T_0 \\ S_{DL}/T, & T > T_0 \end{cases} \tag{4}$$

In addition, through the aforementioned processes, the site-specific uniform hazard response spectrum corresponding to a given frequency of exceedance of plant site can be determined.

Conclusions

This report presents an overview of the entire procedures on seismic hazard analysis for plant site. Details on the deliberations and decision making in the determination of parameters for hazard analysis, including: seismogenic zones, seismicity parameters, and attenuation and rupture length relations, are described. Since the seismogenic zones used for the seismic hazard analysis were based on the considerations of tectonics and past seismicity patterns in the region was also investigated in this study.

The uniform hazard response spectrum (UHRS) is determined based on the spectral accelerations corresponding to a given probability of exceedance in the probability seismic hazard curves. The accuracy of the estimation for spectral accelerations at a specific site strongly depends on the geologic condition underlying the site. Therefore, the local site effect should be taken into account for a seismic hazard analysis. In this study, for the probabilistic seismic hazard analysis, the local site effect is considered using both the site-specific attenuation relationships and the local site amplification factor. Earthquake database around plant site is used to calibrate the local site effect. In this study, an approach was provided to develop the site-specific design response spectrum for plant site. Finally, the damage earthquake data near the specific site are used to refine the uniform hazard response spectrum at several periods of the seismic characteristic of the site.

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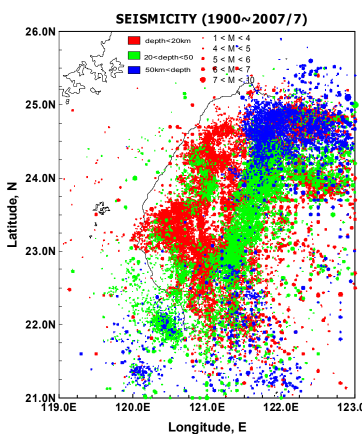


Figure 1. Seismicity map of Taiwan

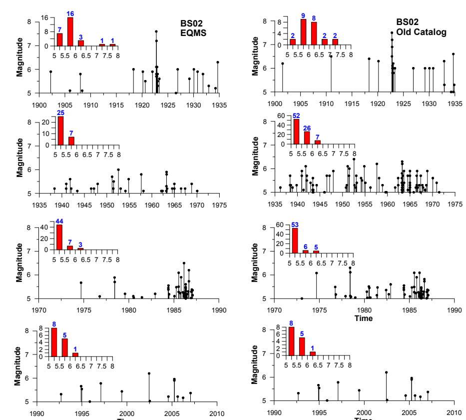
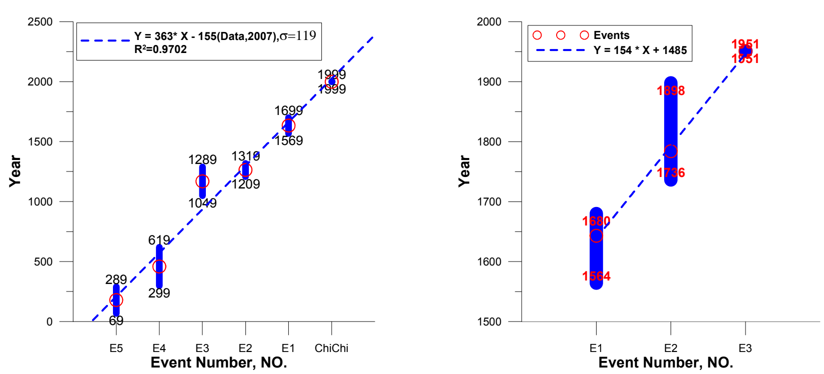


Figure 2. Comparison of Catalog of EQ.



(a)Chelungpu fault (b) Longitudinal Valley fault

Figure 3. The occurrence time of characteristic earthquake based on the pale-seismological study.

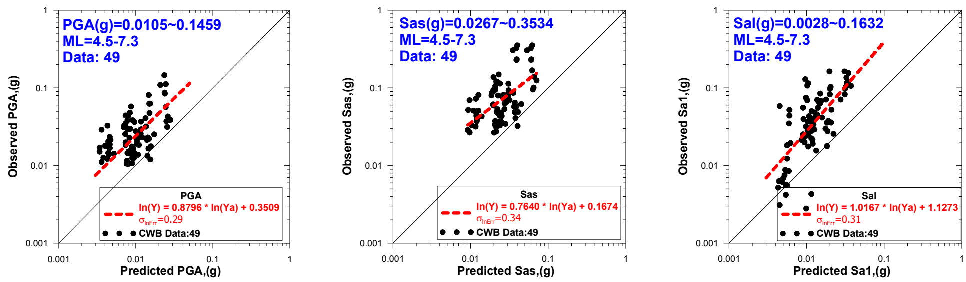


Figure 4. The site amplification factor for plant site

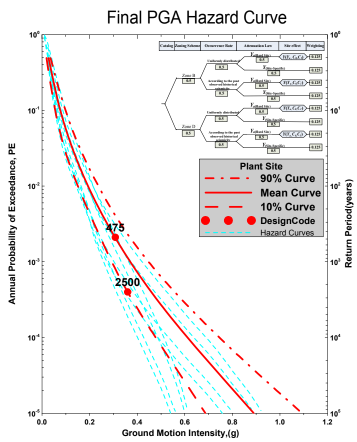


Figure 5. The final best estimate mean hazard curves for plant site

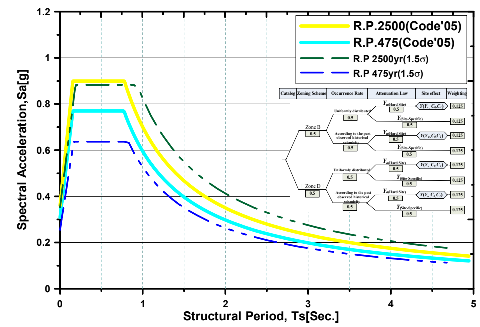
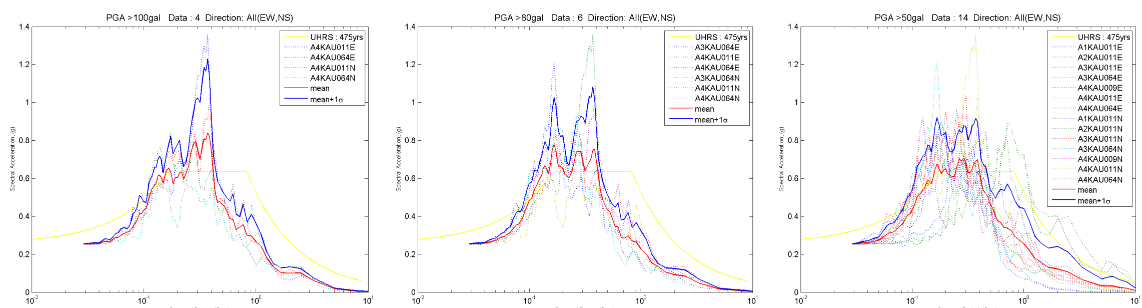


Figure 6. The seismic design spectrum for plant site



PGA ≥ 100gal PGA ≥ 80gal PGA ≥ 50gal

Figure 7. Comparison of the response spectrum of earthquake recorded near the site and the UHRS. All the earthquake records were normalized to PGA=0.255g.

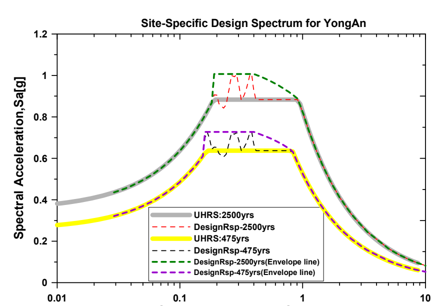


Figure 8. The site-specific design response spectrum for special return periods

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