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Vladimir Sokolov
Geophysical Institute, Germany

Chin-Hsuing Loh
NCREE, Taiwan

Kuo-Liang Wen
Institute of Geophysics, NCU, Taiwan

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Sokolov Vladimir
Geophysical Institute, Hertzstr. 16,
Karlsruhe, 76187, Germany

Loh Chin-Hsuing
NCREE, 200, Sec. 3, Hsinhai Rd.
Taipei, Taiwan

Wen Kuo-Liang
Institute of Geophysics, NCU
Chung Li, Taiwan, 30254

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ABSTRACT

An integrated approach for evaluating "site-dependent" seismic hazard in terms of ground-motion parameters, which are used for engineering purposes, is presented. The method is based on the probabilistic seismic hazard analysis in terms of Fourier acceleration spectra. A scheme that allows conversion of the Uniform Hazard Fourier spectra to "hazard-compatible" peak ground acceleration (PGA), and Uniform Hazard response spectra is described. The method has been applied for preliminary probabilistic microzonation of the Taipei basin (the Taipei city). The source, path and site effects are characterized separately on the basis of the analysis of large collection of ground-motion recordings obtained since 1991 in Taiwan area. The probabilistic microzonation maps of the Taipei basin were compiled for various return periods and were compared with the data from recent strong earthquakes. It has been shown that Peak Ground Acceleration and amplitudes of the Uniform Hazard Response spectra strictly depend both on the local site conditions and on the characteristics of seismicity (the depth and location of earthquakes, and azimuthal direction of incident excitation). Therefore, one single building code is not adequate for the whole basin area. The obtained "Region & Site & Return period-dependent" estimations may be used as a reliable basis for building code provisions and engineering decisions.

KEYWORDS

Seismic hazard analysis, local site effect, design ground motion parameters

INTRODUCTION

The problem of accounting for local soil effect on earthquake ground motion is especially urgent when assessing seismic hazard — recent needs of earthquake engineering require local site effects to be included into hazard maps. At the present, there is no doubt that it is necessary to construct "site-specific" design parameters reflecting the influence from different magnitude events at different distances that may occur with a certain probability during the lifetime of the construction, as well as the variety of local site conditions. Probabilistic seismic hazard analysis (PSHA) is the efficient tool for this purpose, because it produces integrated description of the influence from all damaging events at all possible locations with respect to a specific case.

Several approaches have been used to include local site effects into PSHA. One of them is based on introduction of a "site coefficient" to modify PGA or spectral shape (e.g., Borcherdt, 1994). It requires the site classification depending on the geotechnical properties (shear-wave velocity), or geological conditions. Obviously, these "site coefficients" depend on the frequency content and intensity of the input motion and, therefore, on earthquake magnitude, distance and regional peculiarities of the seismic wave excitation and propagation. The simplified classification of a site geology is not applicable in the cases of deposits which are characterized by complex structure and configuration of bedrock surface, for example, alluvium-filled valleys and canyons. In the second approach, the empirical attenuation relations developed for different site conditions are used. Trifunac (1990) compiled microzonation maps in terms of UHS on the basis of attenuation model, which depends on the depth of sedimentary deposits. Petersen et al. (1997) used different attenuation relations to calculate hazard for alluvium, soft rock and hard-rock site conditions. It is not possible to obtain the attenuation functions for a variety of local soil conditions, and the results reveal the gross features of the geology.

When estimating seismic hazard for urban territories, we face before following problems. First, the extended areas covered by large cities are characterized by a variety of local geological and geotechnical conditions, as well as of the site position relatively to the source zone. Second, the requirements to optimize engineering decision demand for estimation of ground motion parameters for different return periods concerning the structures of different importance factors (from 200-2000 years for ordinary structures to 1000-10000 years for critical facilities). When estimating hazard in terms of response spectra it is necessary to obtain a family of response spectrum curves corresponding to different values of damping. The range of the damping ratio in structural systems lies between 2 % and 20 % of critical damping depending on the material employed and the construction of the structure. The capacity spectrum method which is used for a performance evaluation (e.g. Krawinkler, 1995) requires both the 5% response spectra and the highly damped ones.

The probabilistic seismic hazard analysis which is based on Fourier acceleration spectra (FAS) seems to meet the requirements of earthquake engineering practice to estimate so-called "site & region & return period - specific" ground motion parameters. The use of the FAS has several advantages. On the one hand, when using the Fourier amplitude spectrum as a basic input in seismic hazard analyses, it is possible to utilize a variety of the models and approaches both for evaluation of this parameter, as a function of magnitude and distance (e.g., Boore, 1983, 1987; Atkinson and Mereu, 1992; Beresnev and Atkinson, 1997), and for consideration of local site conditions (e.g., Bard, 1995). On the other hand, the term "design ground motion parameters" also includes seismic intensity as a useful and simple quantity describing the damage due to earthquakes, and the intensity distribution patterns or probabilistic intensity maps are widely used for loss estimation. The PSHA in term of macroseismic intensity is generally performed using empirical relationships between intensity, earthquake magnitude and distance, or by converting PGA hazard maps to intensity. However, seismic intensity, besides the amplitude, is an expression of the duration and frequency content of ground motion. The technique which is based of the recently established relationships between intensity and the Fourier amplitude spectra (Sokolov and Chernov, 1998) allows to evaluate absolute values of site-dependent intensity directly using the spectra of ground acceleration.

The purposes of this paper are to give short description of the method, and to present some results of the method utilization on the example of the Taipei city.

DESCRIPTION OF THE METHOD

The method is based on Cornell's approach to probabilistic seismic hazard assessment (Cornell, 1968), which incorporates the influence of all potential sources of earthquakes and the activity rate assigned to them. However, the computational scheme (Sokolov, 2000) differs somewhat from the classical one. For a given earthquake occurrence, the probability that a ground motion parameter X will not exceed a particular value x can be computed using the total probability theorem, that is

$$P[X \le x] = P[X \le x \mid Y]\,P[Y] \qquad (1)$$

where Y is a vector of random variables (earthquakes of magnitude M and distance R) that influence X. Assuming that M and R are independent, the probability can be written as

$$P[X \le x] = \iint P[X \le x \mid m, r]\, f_M(m) f_R(r)\, dm\, dr \quad (2)$$

where $P[X \le x \mid m, r]$ is obtained from the predictive relationship and $f_M(m)$ and $f_R(r)$ are the probability density functions for magnitude and distance, respectively. When performing PSHA using classical scheme, it is necessary to determine the temporal distributions of earthquake recurrence and source-to-site probability distributions for source zones. In our scheme the probability density functions $f_M(m)$ and $f_R(r)$ are not used, and every potential earthquake is consider as a separate event. Thus, Eq. (1) may be rewritten as

$$P[X \le x] = P[X \le x \mid Y(m_1, r_1)] \times P[X \le x \mid Y(m_2, r_2)] \times \ldots \times P[X \le x \mid Y(m_N, r_N)] \qquad (3)$$

where $Y(m_i, r_i)$] is the potential earthquake with magnitude $M_{min} \le m \le M_{max}$ and distance $R_{min} \le r \le R_{max}$. The possible earthquakes are specified by geometry (in three dimensions), and a function describing rupture area as a function of magnitude. At the same time, the earthquakes occur within the areas (source zones) which are characterized by maximum possible magnitude M_{max}. In this case, the active fault is considered as a narrow source zone rather than a line.

Let us assume that the level of seismic hazard is controlled by the total influence of all earthquakes that may occur in the region under study, and that the characteristics of ground motion expected during an earthquake of given magnitude M and distance R are lognormally distributed with standard deviation σ_x. Then, for a single earthquake of magnitude $M = m$, focus depth $H = h$, and distance $R = r$ the probability that ground motion characteristic X will not exceed a particular value x may be estimated as follows:

$$P_{N(M=m;R=r;H=h)=1}[X \le x] = \frac{1}{\sigma_x\sqrt{2\pi}} \int_{x_{min}}^{x} \exp((x-a)^2/2\sigma_x^2)dx \quad (4)$$

where a is the mean value of $\log_{10} X$ for an earthquake of given M and R; and x_{min} is of sufficiently small value. Sources of ground motion parameter uncertainty are inherent randomness in the source rupture, the characteristics of wave propagation path, and variability in the subsoil and geological conditions. Therefore, strictly speaking, standard deviation σ_x is a function of magnitude, distance, soil condition and oscillator frequency. Let us also assume that value a_R represents ground motion parameter for a "reference", for example hard rock, site. Thus, for a non-reference site, parameter a in Eq. 4 may be determined as $a = a_R + \Psi'$, where Ψ' is a site coefficient. If the parameter a represents the Fourier amplitude spectra at a given frequency f, then the local site effect can be described by the site/reference spectra spectral ratios. In this case $a(f) = a_R(f) + \log_{10}\Psi(f)$, where $\Psi(f)$ is the spectral amplification. To consider the uncertainty of the site response, the spectral amplification should be described as a random variable, and Eq. 4 may be rewritten as follows

$$P_{N(M=m;R=r;H=h)=1}[X \le x] = \sum_{\Psi_{min}}^{\Psi_i} \{[\frac{1}{\sigma_x\sqrt{2\pi}} \int_{x_{min}}^{x} \exp((x-a)^2/2\sigma_x^2)dx] * P[\Psi = \Psi_k]\} \qquad (5)$$

where $P\ [\Psi = \Psi_k]$ is the probability that the spectral amplification equals Ψ_k. Actually, it is possible to use different spectral amplification values for small and large, nearby and distant earthquakes taking into account the peculiarities of the site response that may depend on intensity of the motion and earthquake characteristics (azimuth, earthquake depth, etc.).

To make the results of probabilistic seismic hazard assessment clearer and more useful for engineering purposes, the so-called deaggregation procedure is used (e.g., McGuire, 1995). The hazard is represented by a single, or several earthquakes of certain M and R (so-called "dominant earthquakes") that determine the motion in a given frequency range. Ground-motion parameters for engineering purposes can be obtained (generated or selected) for these (M,R) pairs. Generally, a single "dominant earthquake" will not reasonably represent the uniform hazard spectrum, and multiple design events should be considered.

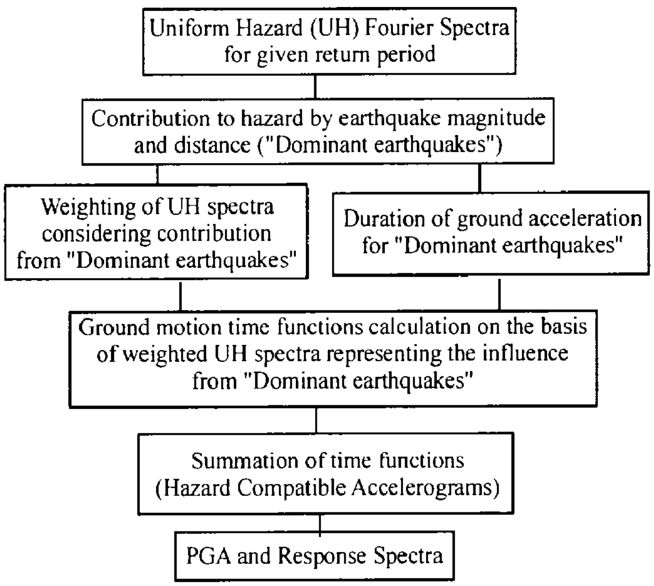

Fig. 1. Scheme of probabilistic seismic hazard assessment in terms of peak ground acceleration (PGA) and response spectra on the basis of Fourier amplitude spectra.

Since a necessary ground motion parameter can be extracted from the acceleration time series, in our scheme (Fig. 1), the "dominant earthquakes", which were determined for a given return period, are used for generating ground motion time series for the whole frequency band studied on the basis of "site-specific" Uniform Hazard Fourier spectra (UHFAS). First, the relative contribution to Fourier spectra hazard by earthquakes of M and R for various return periods at different frequencies is determined. The Uniform hazard Fourier spectrum should be weighted taking into account the contribution to produce the "characteristic" spectra that represent influence from "dominant earthquakes" and take into account their recurrence. The "dominant earthquake compatible" ground motion time series are generated using stochastic approach on the basis of these spectra. Actually, these time series ("hazard-compatible" or "Uniform Hazard accelerograms") do not represent ground motion for a single earthquake, but may be considered as a combination of the motion components in the chosen frequency band, parameters of which (spectral amplitudes) will not be exceeded with a certain probability in a specified time period. Peak ground acceleration (PGA) and response spectra which are determined using these time histories are essentially the "hazard-compatible" estimations.

GEOLOGICAL STRUCTURE OF THE TAIPEI BASIN

The Taipei basin is a triangular alluvium structure, and the area (about 240 square kilometers) is almost flat at an altitude above the sea level of less than 20 meters. The geological structure inside the basin consists of Quaternary layers, which were separated into five stratigraphic formation, above tertiary base rock. Figure 2 shows a scheme of the Taipei basin, a cross section through the basin, and stations of the Taipei strong motion observation network (TSMIP). The average values of S-wave velocity change from 170 m/sec, for the upper Quaternary layer, up to 650 m/sec for the deepest layer, and the base rock is characterized by the average S-velocity of 1200 m/sec.

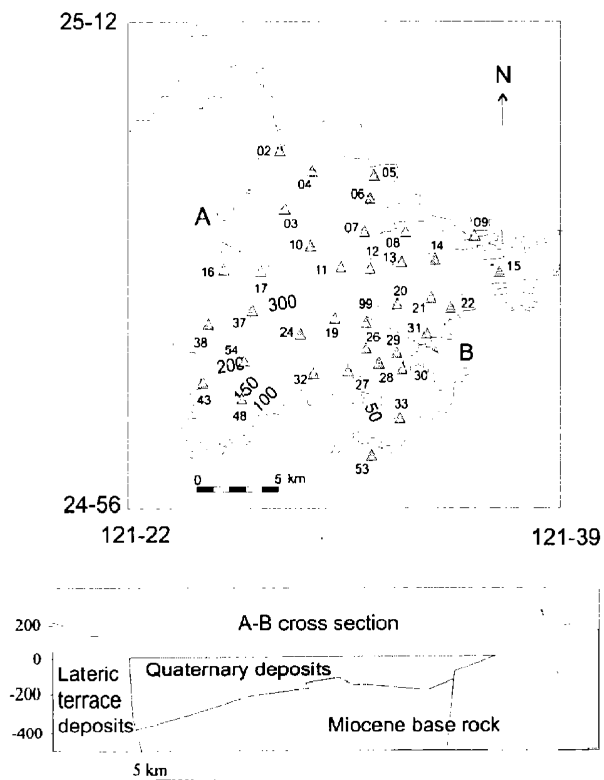

Fig.2. Map of the Taipei basin and location of the TSMIP network stations (triangles). Numbers indicate the station codes. The dotted contours show the depth in meters to the base rock surface in the Taipei basin.

INPUT DATA

The input data that are crucial in PSHA are the parameters of earthquake source zones (maximum magnitude, distribution of the hypocentral depth and earthquake recurrence), ground motion attenuation relationships, and site response characteristics. The schemes of seismic source zones (Loh and Jean, 1997) for shallow (hypocentral depth H ≤ 35 km) and deep (H > 35 km) seismicity are shown in Fig. 3.

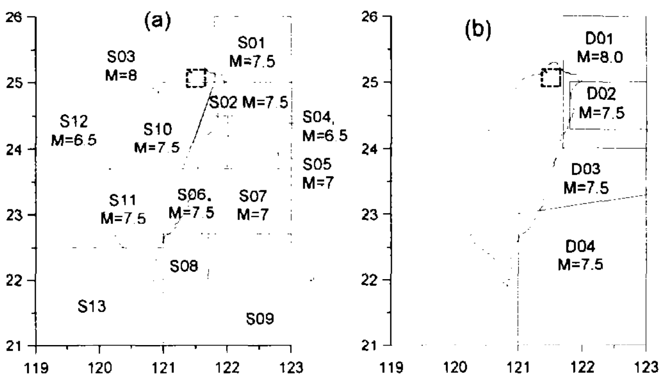

Fig. 3. Schemes of seismic source zones with estimated maximum magnitudes M for shallow (a) and deep (b) seismicity in the Taiwan area. The dashed lines show location of the Taipei basin.

It is necessary to note that these schemes, as well as the earthquake occurrence models for every zone, were obtained on the basis of the data that were available before the recent strong Chi-Chi earthquake (M_L=7.3, September 21, 1999) occurred in the central part of the island (zone S10). The energy of the Chi-Chi earthquake conforms to the estimated maximum magnitude for the zone, however the recurrence of strong events in this region, which was estimated using earthquake catalogues and was used in this study, may be understated. The study of source scaling and attenuation models in the Taiwan area (Sokolov et al., 1999, 2000a) revealed that the acceleration spectra of the most significant part of the records, starting from S-wave arrival, for hypothetical "*very hard rock*" sites in the Taiwan area can be modeled accurately by the single-corner frequency Brune ω^{-2} source model with magnitude-dependent stress parameter $\Delta\sigma$ (Tsai, 1997). Frequency-dependent attenuation of spectral amplitudes with distance may be described using quality factor $Q = 225 f^{1.1}$ for deep earthquakes and $Q = 125 f^{0.8}$ for shallow earthquakes, and a kappa filter (κ = 0.03-0.04) may be used to modify the spectral shape. These models were obtained on the basis of 1380 acceleration records obtained during 176 earthquakes (4.5 ≤ M ≤ 6.5) which occurred since 1991 at distances of up to 200 km. It has been found also that the spectral models, combining with regional duration model, provide a satisfactory prediction of PGA values for the case of the recent strong (M_L=7.3) Chi-Chi earthquake.

The site effect in the Taipei basin was analyzed on the basis of recordings of TSMIP network (Sokolov et al., 1999, 2000b). Records from 66 earthquakes obtained at 35 stations were used. The approach consisted in calculating spectral ratios between spectra of actual earthquake records (horizontal components) and those modeled for a hypothetical *very hard rock* (VHR) site. Actually, these spectral ratios reflect the difference between idealized source scaling and attenuation models and real recordings. Besides local site response, the spectral ratios include effects of source rupture peculiarities and inhomogeneous propagation path. Horizontal-component site-amplification data were obtained within the frequency interval 0.4 Hz to 12 Hz. The ensemble averages of the site response estimation are consistent with theoretical modeling of the amplification curves both in amplitude, resonance frequencies and overall shape. It has been found also that the amplitude and shape of spectral ratios may be different for deep and shallow events. These spectral ratios were further used along with source scaling and attenuation models for "site-dependent" seismic hazard assessment.

RESULTS AND DISCUSSION

The Uniform Hazard Fourier amplitude spectra (UHFAS) of ground acceleration estimated for condition of "very hard rock" site for the central part of the Taipei basin are shown in Fig. 4. These estimations have been made assuming standard deviation σ_x = 0.3 log unit (Eq. 4) of the spectral amplitudes. It is seen that UHFAS levels for deep and shallow seismicity are approximately equal for the low (f < 0.6-0.8 Hz) frequencies, and the spectral amplitudes for deep seismicity are higher for the frequencies more than 0.8-1.0 Hz. This phenomenon can be explained by applying different attenuation models for the shallow and deep earthquakes.

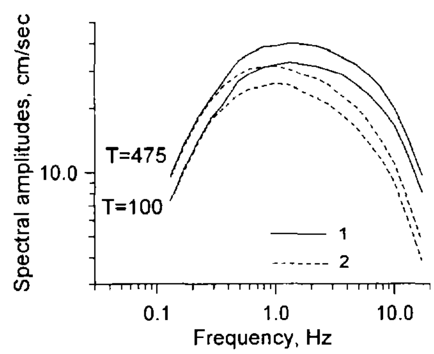

Fig. 4. Uniform Hazard Fourier acceleration spectra (rock site, central part of the Taipei basin) which were estimated for return period T using data for deep (1) and shallow seismicity.

The relative contribution to Fourier spectra hazard was determined to estimate the influence from possible earthquakes in different seismogenic zones. It has been found that for return period 475 years (10% probability of being exceeded during 50 years) the hazard from deep earthquakes is determined by earthquakes occurred in the zone D02 (Fig. 3), and the contribution depends of the frequency of ground motion. The long-period motions are determined by large (M=8.0) events that may occur in the zone at distances R > 100 km. Earthquakes of M < 8.0 contribute significantly in high-frequency domain (f > 1 Hz). The hazard from shallow events is determined by the influence from zones S02, S03 and S10. The distant events of magnitude M=8.0 (zone S03) contribute to hazard in low-frequency domain (f <1 Hz), intermediate- and high-frequency vibrations (f>1 Hz), are determined by earthquakes of magnitude M=7.0 – 7.5 that may occur in the zones S02 and S03, and nearby earthquakes of M=6.0-6.5 (zone S10) bring a certain contribution to hazard in high-frequency domain (f>3-4 Hz). We should note that, accordingly with the data, which were available before the Chi-Chi earthquake, it was accepted that the strong earthquakes in the zone S10 were characterized by very low probability of occurrence. Our scheme of the "dominant earthquakes" determination takes into account the occurrence of the earthquakes and, therefore, it has been revealed that the influence from large and very infrequent events in the central part of the island (zone S10) may be neglected.

The Uniform Hazard Fourier spectra and the frequency-dependent characteristics of the contribution to hazard were used for calculation of "weighted" spectra representing influence from "dominant earthquakes". These spectra produce a basis for calculation of the time functions summation of which produces "hazard-compatible" accelerograms. The stochastic simulation was used, and the ground motion duration values ($\tau_{0.9}$), which are necessary in this approach, were estimated using the regional relationship proposed by Wen and Yeh (1991)

$$\tau_{0.9} = 0.430\ exp\ (0.504\ M_L) \pm 2.749 \qquad (6)$$

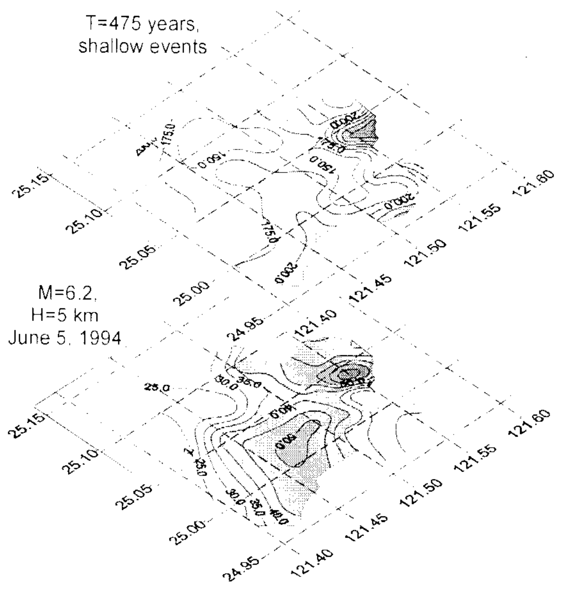

Fig. 5. Comparison of the PGA (cm/sec2) distribution along the Taipei basin: hazard calculation for shallow events and real earthquake.

In order to obtain "site-dependent" estimations, the Uniform Hazard Fourier spectra were calculated for every station of TSMIP network, for which the site response characteristics were studied (Sokolov et al., 2000b). "Hazard-compatible" peak ground acceleration values and response spectra were estimated using the described scheme (Fig. 1) for these sites.

Figures 5 and 6 show distribution of PGA values along the Taipei basin estimated for return period 475 years for shallow and deep seismicity. These schemes are compared with the variation of maximum amplitudes observed during two large and distant events: June 5, 1994, M_L=6.4, H=5 km, and June 25, 1995, M_L=6.5, H=40 km.

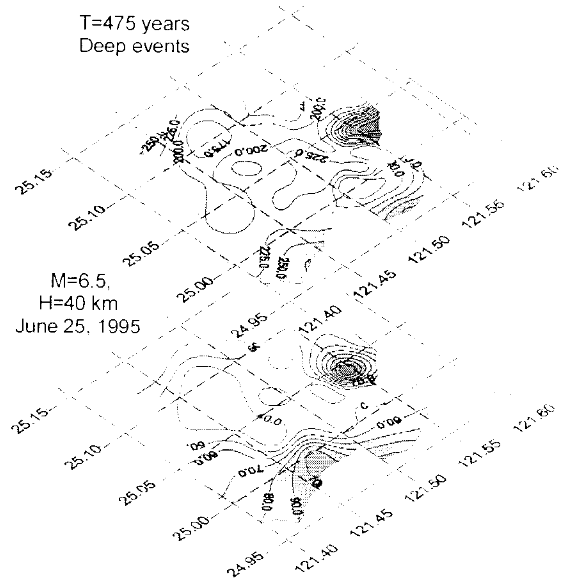

Fig. 6. Comparison of the PGA (cm/sec2) distribution along the Taipei basin: hazard calculation for deep events and real earthquake.

Of course, we should not expect an excellent coincidence between the PGA distribution patterns during the real earthquakes and those obtained by seismic hazard calculations. The averaged spectral ratios (Sokolov et al., 2000b) have been used in the hazard assessment, therefore the "site-dependent" hazard estimations is believed to reflect general features of ground-motion parameter distribution in the studied area. However, it can be seen that the calculated PGA patterns both for shallow and deep seismicity generally agree to the empirical ones and they reveal the lowest PGAs in the northern and southeastern parts of the Taipei basin. The PGA values increase when approaching the north and south edges, and the southeastern part of the basin is characterized by the highest PGA values.

The "site-dependent" Uniform Hazard response spectra (UHS) were estimated in frequency range 0.4-12 Hz. Figure 7 shows comparison between UHS curves for typical site conditions, namely: station TAP03 – deep Quaternary deposits (thickness about 200-125 m), and station TAP15 – shallow deposits (thickness less than 50 m). It can be seen that the amplitude and the shape of UHR spectra depend both on local site conditions and on the characteristics of seismicity (shallow and deep earthquakes). In general, shallow-soil sites near the Taipei basin edges are characterized by the high low-period level of the spectra. The spectral amplitudes for deepest part of the basin are higher than those estimated for deposits of the intermediate thickness. However, some shallow-soil sites may also reveal the high low-frequency spectral amplitudes for shallow earthquakes. Therefore, one single building code design spectrum is not adequate for the whole basin area.

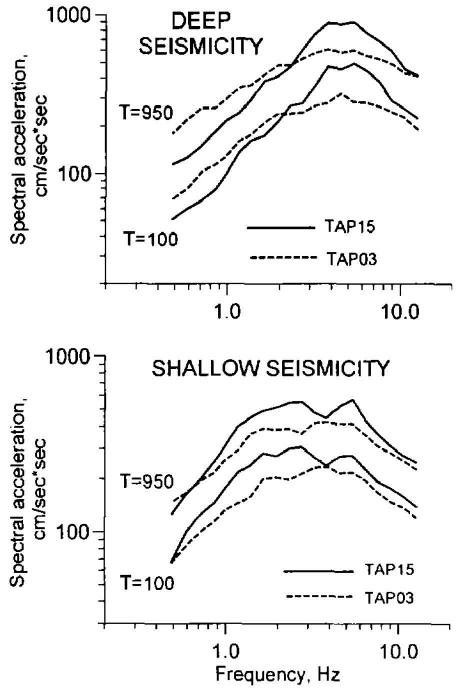

Fig. 7. Comparison of 5% damped Uniform Hazard response spectra estimated for different site conditions (see text).

It is necessary to note, that the local site response in the Taipei basin was studied using the records from earthquakes located to the Southeast of the basin. The recent strong Chi-Chi earthquake of September 21, 1999 (M_L=7.3) produced the basis for study the influence of azimuthal direction of incident excitation on the basin response. This is a topic of future research.

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