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UNIFIED APPROACH TO SEISMIC HAZARD ASSESSEMENT: FROM EVALUATION OF CHARACTERISTICS OF FUTURE EARTHQUAKES TO SITE- AND TIME-DEPENDENT DESIGN INPUT GROUND MOTION PARAMETERS

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SUMMARY

The paper describes an integrated approach to seismic hazard assessment, which was applied for the Taiwan region. First, empirical models for ground motion estimation were obtained using records from recent (1993-1999) earthquakes. The database includes strong-motion data collected during the Chi-Chi earthquake (M=7.6, 21 September 1999) and large (M=6.8) aftershocks. The ground-motion database was also used for evaluation of generalized site amplification functions for typical soil classes (B, C and D). Second, theoretical seismic catalogue (2001-2050) for the Taiwan region had been compiled using numerical models of dynamic deformation of the Earth' crust and seismic process. The models were developed on the basis of available geophysical data that include regional seismic catalogue. Third, the region & site & time-dependent seismic hazard analysis, which is based on schemes of probable earthquake zones evaluated from the theoretical catalogue, regional ground motion models, and local site response characteristics, has been performed. The seismic hazard maps are compiled in terms of Peak Ground Acceleration (PGA) and Response Spectra (RS) amplitudes. The maps show distribution of amplitudes that will not be exceeded with certain probability in condition of typical soil classes during all possible earthquakes that may occur in the region during time period of 2003-2025. The approach allows introducing new parameter that describes dependency of seismic hazard on time, so-called "period of maximum hazard". The parameter shows the period, during which every considered site will experience the maximum level of earthquake ground motion.

INTRODUCTION

During the last 10-20 years large earthquakes caused massive loss of human life and extensive physical destruction throughout the world (Iran, 1990; Japan, 1995, Turkey, 1999; India, 2001, etc.). One of the

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obvious methods to reduce the loss of life that occurs in large earthquakes would be to predict the earthquake (short-term prediction) and evacuate people before the earthquake occurs. Efforts to predict earthquake have been made since the 1950s; however the problem is still waiting to be resolved. At the present state of knowledge, the proper level earthquake-resistant design seems to be one of the most effective ways to prevent grave consequences of the earthquake. The design is based on characteristics of potentially dangerous earthquakes around the site. One of the goals of Seismic Hazard Assessment (SHA) is specification of site and region-dependent engineering (or design) ground motion parameters. Evaluation of location and characteristics of future earthquake zones or the long-term prediction (several years or decades), is also considered as a crucial part of SHA.

Seismic hazard assessment may be divided into two general approaches, namely: consideration of particular, so-called, "scenario" earthquakes; and probabilistic ground-shaking hazard taking into account characteristics of all potentially dangerous earthquakes around the site. The both approaches are widely used in risk quantification and modeling (e.g. Coburn [1]). Such activities, especially emergency management and earthquake insurance, need also information of most likely time period of earthquake occurrence. Earthquake loss estimations should consider multiple events that can affect the studied area during certain time period. In other words, it is necessary to introduce time-dependent factors into seismic hazard assessment. The probability of occurrence of large earthquakes is being estimated on the basis of various regional data and ideas about physical processes that cause earthquake (e.g. WGCEP [2], Reasenberg [3]. Various models of time-dependent earthquake occurrence are also considered in probabilistic seismic hazard studies (e.g. Papaioannou [4]).

There are two types of uncertainty in seismic hazard analysis, namely: I - the uncertainty connected with effect of a future earthquake, or uncertainty in ground motion parameter evaluation for a particular earthquake, region and site condition; II - the uncertainty due to unpredictable nature of a future earthquake (*when, where, how large*). The first uncertainty is caused by uncompleted knowledge and may be reduced by using additional data. For example, the Chi-Chi earthquake ($M_L = 7.3$, $M_W = 7.6$, September 21, 1999, Taiwan) and its aftershocks produced a rich set of more than 1000 ground motion recordings, which are currently under extensive study (Shin [5]). At present there is a common opinion that the only way to reduce the second type of uncertainty is the development of several numerical models, which approach the reality. In most cases the definition of the earthquake source zone parameters (configuration, maximum possible magnitudes, and earthquake recurrence) is carried out on the basis of the historical data, i. e. using the events, which were already occurred. Statistical properties of the known seismicity are assumed to be stationary in time and space, and therefore should apply in the foreseeable future. There are many examples, including the case of the above-mentioned Chi-Chi earthquake, when the erroneous estimation of these parameters led to the grave consequences.

In this paper we describe an integrated approach to seismic hazard assessment, which was recently (1999-2002) applied for the Taiwan region. The region is characterized by high seismicity, and earthquakes occur up to about 200-300 km (Figure 1). Taiwan has repeatedly been hit by large earthquakes and at least 19 damaging earthquakes occurred there during the twentieth century (Shin [5]). The worst of the earthquakes, the Chi-Chi earthquake, caused heavy damage in the central and western part of Taiwan. The official casualty figure included 2470 dead, more than 11,000 injured, and more than 100,000 structures destroyed. The most recent, so-called 331 Hualien earthquake (M_L=6.8, 31 March 2002) occurred approximately 100 km to southeast from the city of Taipei (Loh [6]). The earthquake caused collapsing of residential building in the city and falling of construction facilities from the top (56 stories) of Taipei Financial Center that was under construction. Five construction workers were killed.

When performing assessment of seismic hazard for the region, we made attempts to reduce the both uncertainties mentioned above. The parameters of the future earthquakes are evaluated on the basis of dynamic 4D (*x, y, z, t* - location, depth, time of occurrence) model for the process of Earth crust deformation and 5D (*x, y, z, t, M* - location, depth, time of occurrence, magnitude) statistical model of seismicity. The final purpose of the models application is to compile so-called "theoretical seismic catalogue" of future earthquakes, which could be used as a basis for evaluation of the future seismic zone configuration and maximum possible magnitude. The catalogue provides necessary information for seismic hazard assessment in terms of design input ground motion parameters, which is based on Fourier Amplitude spectra (FAS) of ground acceleration. The approach allows taking into consideration regional (source scaling, attenuation relation) and local (site condition) peculiarities of seismic ground motion. It is possible to obtain the results in terms of seismic intensity, peak acceleration, response spectra and characteristic accelerograms using a common ground motion model (Sokolov [7]). The features of input ground motion models were analyzed and quantitatively described for the Taiwan region on the basis of recent earthquakes including the large M_W=7.6, 1999 Chi-Chi earthquake.

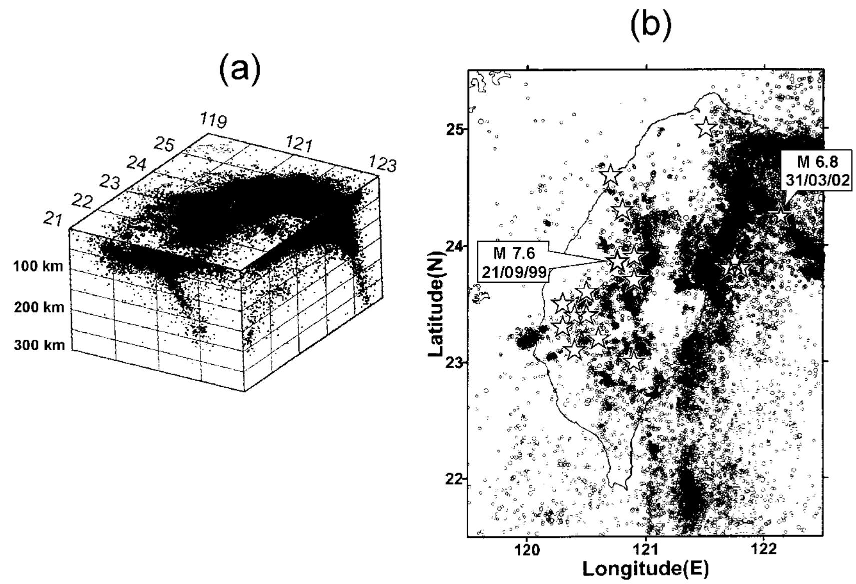

Figure 1. Seismicity of Taiwan. (a) A 3D plot showing hypocenters of earthquakes occurred during 1973-2000 (M > 3). (b) A scheme of epicenters for events of M > 3 (1990 to 1999). The 19 damaging earthquakes in Taiwan during the 20th century are shown as open stars. The figure is taken from Shin [5], and two recent events were added, namely: the Chi-Chi earthquake (21 September, 1999) and the Hualien earthquake (31 March, 2002).

The theoretical catalogue, which allows us to evaluate parameters of future seismic source zones, regional spectral models, and generalized site response characteristics are used, as input parameters, for evaluation of ground motion characteristics for generalized soil classes (B, C and D) throughout Taiwan Island. The compiled schemes show Peak Ground Acceleration and Response Spectra that will not be exceeded with certain probability (50%, 84% and 97%) during time period of 2003-2025. We also introduce new parameter that describes dependency of seismic hazard on time, so-called "period of maximum hazard", which is of particular interest of seismic risk management and insurance business.

FUTURE EARTHQUAKES ZONATION

Basic principles and short description of the models

The slow deformation of the Earth crust is the main source of the crust fracture and fast energy release in the form of earthquakes. A comprehensive study of the process became possible after establishment of satellite system for direct coordinate measurement (Global Positioning System or GPS). The data obtained during the *direct* observations of deformation and by analysis of *indirect* indications (gravitational, magnetic and electromagnetic fields, elastic properties of geological medium, water level in boreholes, changes of coastline, etc.) suggest that development of deformation of the Earth crust should be considered as a dynamic process, which includes wave-like components (Figure 2).

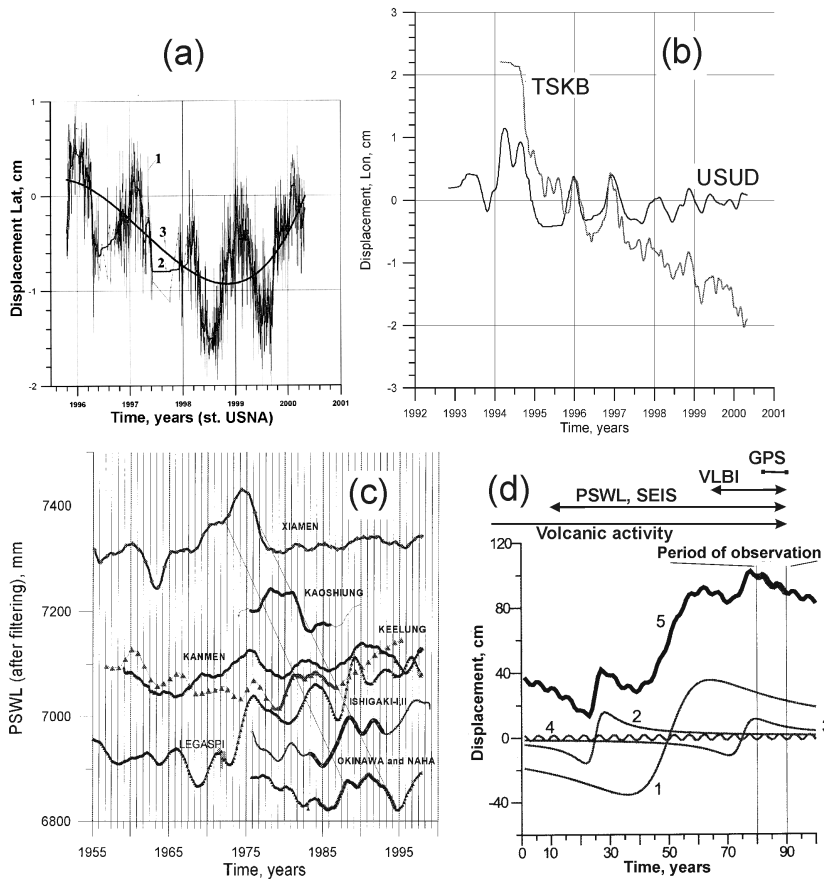

Figure 2. Dynamic nature of the Earth crust deformation. a - typical wave-like components of deformation that could be revealed from the GPS data (station USNA, 38.98N, 76.48W). 1 – observed latitudinal displacements; 2 – curve, which obtained after smoothing (14-points running average), reveals five fast-propagating waves of (probably) seasonal nature; 3 – third-power polynomial shows a slow-propagating wave of deformation. b – examples of synchronous changes (longitudinal displacement) for two closely located stations USUD (36.133N, 138.362E) and TSKB (36.105N, 140.087E). c – example of slow-propagating wave of deformation that was revealed in the PSWL (sea water level) data (zero lines were changed). d - modeled example of the arbitrary separate waves of deformation (curves 1-4) and the summarized (observed) deformation (curve 5). Period of GPS observation is bounded within the lines; arrows show duration of various types of observation.

When analyzing the process of deformation, it is necessary to utilize all kinds of the direct and indirect data that would allow modeling the process in a given volume of the crust. The multidimensional models of the complicated geodynamic processes inside the Earth crust (deformation and seismicity) may be constructed using analytical approximation. Two such approximations (4D and 5D-models) and the technique for the models adjustment to the observed data have been recently proposed by Ovcharenko [8-11] (see also Sokolov [12]). The database for modeling contains basic data of geophysical observation:

seismic catalogues, data obtained by global and local GPS networks, very long base line interferometery (VLBI) data, sea water level observations, high precision leveling, etc.

The general approach for development of the 4D (*x, y, z, t* – geographical coordinates, depth and time) models of geological and geophysical processes is as follows. A function $\boldsymbol{F}$ [$\boldsymbol{p}$, x, y, z, t] is introduced on the basis of available data. The vector $\boldsymbol{p}$ describes parameters of the process. The most of these parameters, as well as the type of the function $\boldsymbol{F}$, are not initially known. It is supposed that the function $\boldsymbol{F}$ reflects the considered geological phenomenon adequately. The problem consists in a search of the vector $\boldsymbol{p}$ on the basis of uncompleted observational data $\{\boldsymbol{F}_i, i = 1, n\}$. When determining the function $\boldsymbol{F}$, we assume, as a basic principle, that the Earth' crust contains the dynamic objects, namely: the wave-like slow-propagating variations of tectonic deformation. The presence of these deformational (stress) waves was suggested by many authors (e.g. Elsasser [13]).

In the 4D-model, for formalized description of complicated non-linear phenomena of the crust deformation, we introduce a special dynamic object, which is further called "Front of Dynamic Deformation" (FDD) (see Figure 2d). We interpret the term "FDD" as a lengthy line-stretched area of extreme or anomalous values of deformation, which propagate inside the crust with velocities ranging from 0.01 km/year up to 1000 km/year. Direction of propagation of the FDD is parallel to direction of displacement and distribution of deformation within the FDD is characterized by alternating signs. In the axial area the absolute values of deformational displacement increase from the area toward the edges of the FDD. When reaching the local maximum, the displacement decreases in asymptotic way. The distance between points on the asymptotic branches, where the amplitudes of displacement are equal to a half of the maximum values, is called "width of FDD. It is possible to show numerical examples of direct instrumental observation of the waves in the form of characteristic non-linear trend of displacement obtained by GPS arrays or PSWL (Persistent Sea Water Level) monitoring (Figure 2a-c). Obviously, we can observe only a complicated result of the waves interaction (Figure 2d).

The possible seismic events could be revealed by analysis of distribution of deformation inside the Earth' crust. Figure 3 shows the results of application of the 4D-model, which was based on the data that were available before the large Chi-Chi earthquake (central part of Taiwan Island, M_W 7.6, September 21, 1999; thrust faulting). The data include GPS and PSWL observation, and seismic catalogue. The development of a narrow zone of intensive compression (depth about 10-20 km) in the central part of Taiwan Island is clearly seen (Figure 3a). The location, shape and absolute values of deformation correspond to the parameters of the Chi-Chi earthquake, and period of the maximum values of deformation corresponds to 1997-2000 years. It is also proposed, as a working hypothesis, to consider seismic events as the peculiar points of the field of dynamic deformation – the interaction of four or more fronts of dynamic deformation. The area of interaction is characterized by complicated distribution of deformation and, therefore, by high stresses. The location of the Chi-Chi earthquake source is clearly fixed by the correspondent zone of interaction of several revealed FDDs (Figure 3b).

The 4D-model is a numerical model of deformation that causes the rupture processes inside the crust. Earthquake magnitude is a characteristic of energy radiated during the rupture. Besides the amplitude of deformation (slip), magnitude also relates with other parameters (fault area, physical properties of rock, etc.) that are not directly considered in the 4D-model. The 4D-model determines location of idealized point that corresponds to interaction of several FDDs. However, it is necessary to consider a certain volume of the crust that is affected by the FDDs. Bearing in mind the dynamic nature of the crust deformation, it is obvious that the rupture may occur *before* or *after*, *near* or *far off* the idealized point of the FDDs interaction. These factors lead to the uncertainties in magnitude, time and location of potential seismic events predicted by the considered deformational model.

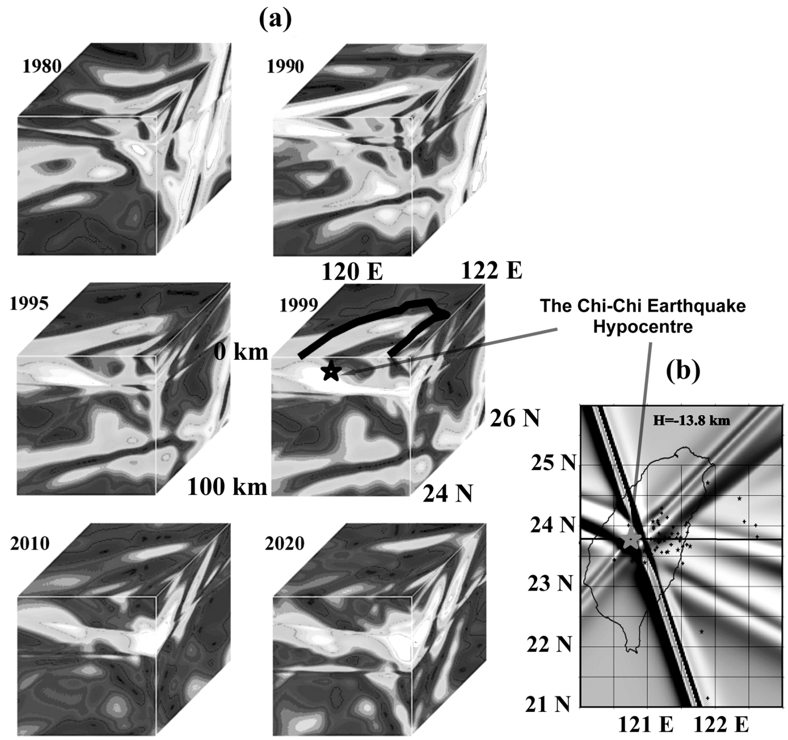

Figure 3. Example of application of the 4D-model for the northern part of Taiwan Island.
a) Absolute vector of deformation; dark areas correspond to the zones of tension deformation, light areas denote the compression zones. The hypocenter of the Chi-Chi earthquake (1999, reverse faulting) is shown by black star. b) The fronts of dynamic deformation (FDD) which were modeled for September 1999, depth 13.8 km. Big star – the Chi-Chi earthquake hypocenter; small stars and crosses denote earthquakes occurred before and after the Chi-Chi earthquake mainshock.

On the other hand, it is naturally to assume that "background" seismicity reflects the peculiarities of the Earth' crust in the given region. Therefore, a statistical formalized 5D-model for seismic process (*x, y, z, t, M* – geographical coordinates, depth, time, magnitude) had been developed on the basis of seismic catalogue only (Ovcharenko [14]). Seismic process is described by a system of dynamic objects, so-called planar dynamic "fronts of seismicity", which were evaluated during specific iterative procedure on the basis of initial observed catalogue.

When the 4D-model of process of deformation and the 5D-model of seismic process are used jointly, it is necessary to determine the peculiar "points" that correspond to each other in the both models. The points are considered as potential seismic events. Magnitude of the event is evaluated by the 5D-model. A scheme of the process is shown in Figure 4.

Results of the models application

Observed seismicity.
From the seismological point of view, the main goal of modeling of the process of dynamic deformation is to compile a complete (M > 4) prognostic or theoretical seismic catalogue for a sufficiently long time period. The catalogue may be further used for purposes of seismic hazard zonation. The schemes of seismic source zones are not strongly influenced by statistical errors of prognostic time of occurrence, location and magnitude of the events. The theoretical catalogue for future 40-50 years for Taiwan region

(119-123 E, 21-26 N) was calculated using the described models. When developing the models, we used GPS data (global and local networks), PSWL observation, and generalized seismic catalogue, which contains more than 29000 events (M > 3) and covers time period from 1900 to 1999.

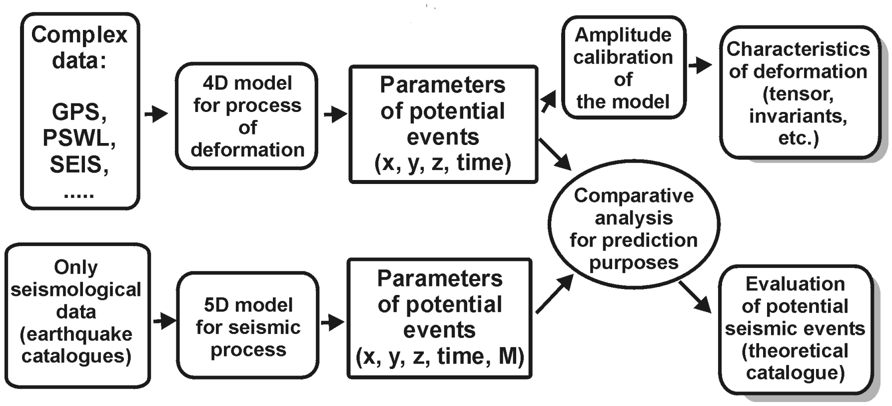

Figure 4. Scheme of earthquake forecasting using the 4D- and 5D-models.

The results of the modeling of the observed catalogue (1900-1999) by the developed models show that the overwhelming majority (94-95%) of seismic events can be modeled with sufficient accuracy (Table 1). However, there are large errors for small number (5-6 %) of theoretical events, which are caused by peculiarities of the applied algorithm and, most probably, due to presence of foreshocks and aftershocks, which could not be entirely considered in the modeling.

Table 1.

Statistical characteristics of the difference between parameters of observed and modeled earthquakes, Taiwan region

Parameter	Standard Deviation (29986 events M_L 3-8)	Averaged Maximum absolute errors (97%)*
Longitude, degrees	0.0042	-0.4; +0.42
Latitude, degrees	0.0067	-0.50; +0.55
Depth, km	2.63	-10, +30
Time, year	0.51	-3.8; +4.5
Magnitude, unit	0.03	-0.3; +0.3

* Difference between parameters of observed and modeled events for the subset containing 97% of all events (29100 events)

Figure 5 shows examples of comparative analysis of the observed and modeled seismic catalogues. That the modeled catalogue provides a good agreement with general characteristics (total number of earthquakes of various magnitudes) of the observed catalogue. Let us also compare parameters (location, time of occurrence, and magnitude) of the largest earthquakes occurred in the Taiwan region during September-December 1999 and the theoretical seismic events predicted by the models (Figure 5b). Location of extended source of the Chi-Chi earthquake with non-uniform distribution of dislocation coincides with two large theoretical consecutive events. Magnitude, location and time of the other strong earthquake, which occurred near the SE coast, almost completely fit the parameters of the predicted event. However, the earthquake of M 6.2 that occurred a month later to the South from the Chi-Chi earthquake area does not exist in the theoretical catalogue. It is possible to assume that large earthquake could produce a local fast-propagating spherical front of deformation (post-earthquake front). The front, in turn, may cause new events (e.g. earthquake of M 6.2, October 1999) due to interaction with the existing FDDs.

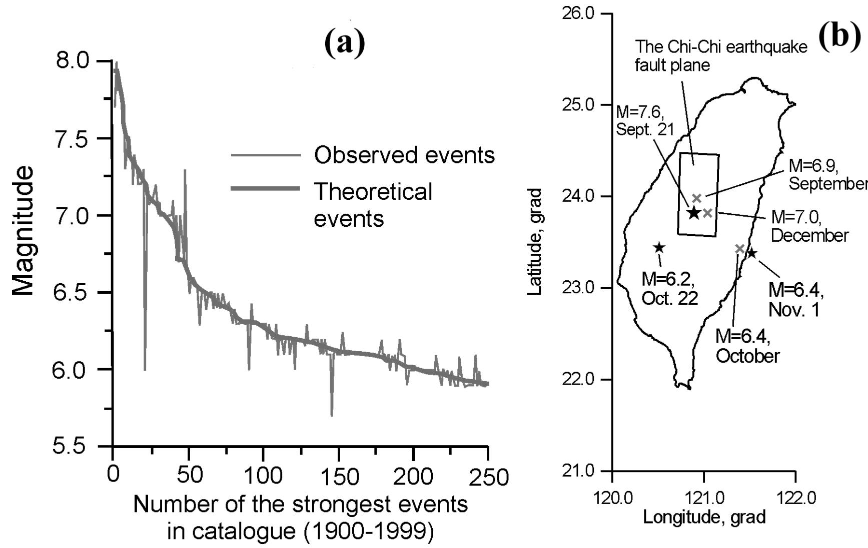

Figure 5. Examples of results of the modeling. (a) Comparison of total number of large observed earthquakes and theoretical events. (b) Comparison of parameters (location, time, and magnitude) of strong earthquakes (stars) occurred in Taiwan region during September-December 1999 (aftershocks of the Chi-Chi earthquake are not shown) and possible seismic events predicted by the 4D/5D-models (crosses).

Theoretical catalogue.

The theoretical catalogue has been compiled on the basis of empirical data obtained before June 2001 (2001.5). For testing purposes, we compare independent data, namely: parameters of observed earthquakes and theoretical events for time period between January 2001 and June 2003. It is necessary to bear in mind that real seismic event may occur before or after the correspondent theoretical event. Thus, when comparing real and theoretical catalogues, it is necessary to use theoretical catalogue calculated for a period that covered sufficiently long interval *before* and *after* the real observation. The condition is not realized at present: we have theoretical catalogue that covers only the interval after the observation.

Figure 6 compares location of epicenters of large (M ≥ 5.9) earthquakes occurred in the region during the considered period and the correspondent events in theoretical catalogue. The difference between location almost for all R-T pairs does not exceed 0.2 degree (20-25 km, Table 2). Three R-T pairs are characterized by large difference between location (more than 0.5 degree) and they are shown as yellow-green pairs. Two real earthquakes (M 6.7 and 5.9) of these pairs occurred in the boundary zones of the studied area. The third real earthquake (M 6.1) occurred in the central part of the island in July 2000 and, most probably, it should be also considered as aftershock of the Chi-Chi (September 1999) earthquake.

Bearing in mind unpredictable character of rupture initiation and propagation, it is necessary to consider the following phenomenon: a single real earthquake may correspond to several theoretical events. By the other words, the rupturing zone of the real earthquake may extend through several points that are considered as theoretical events and that may occur within certain volume during certain time period. An example can be seen in Figure 5b – the Chi-Chi earthquake corresponds to two consequent smaller theoretical events.

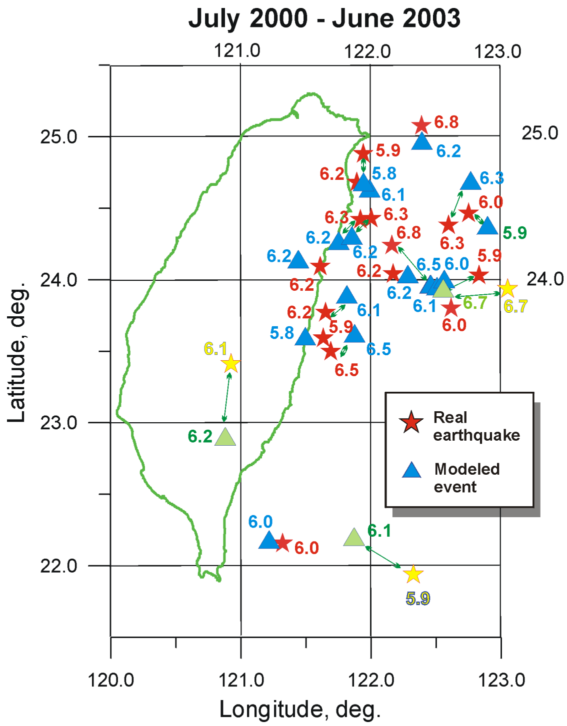

Table 2.
Statistical characteristics of the difference between parameters of large observed and modeled earthquakes, Taiwan region, June 2000 - July 2003.

Parameter	Averaged Maximum absolute errors 14 events M > 5.8
Longitude, degrees	0.25
Latitude, degrees	0.20
Depth, km	12
Time, year	1.2
Magnitude, unit	0.2

Figure 6. Comparison of location of large (M > 5.9) observed earthquakes (stars, July 2000 – June 2003) and events in the theoretical catalogue (triangles).

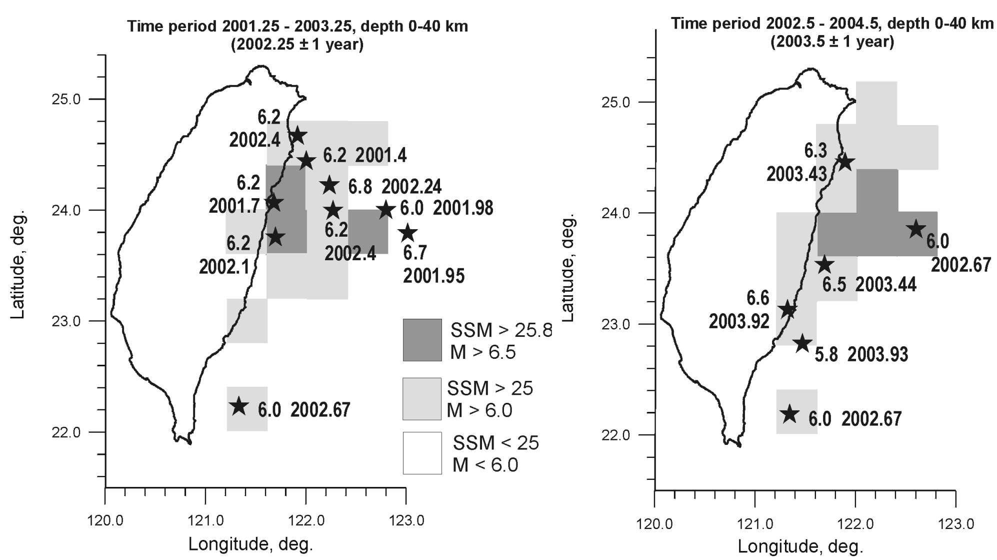

Figure 7. Distribution of summarized seismic moment values (SSM, base 10 logarithm) for shallow theoretical events (depth 0-40 km); considered time period includes observations. Epicenters of large observed earthquakes, magnitude and date of occurrence are shown for comparison. The dates of earthquakes are shown in decimal format: for example, June 2002 corresponds to 2002.5.

Let us consider distribution of summarized seismic moments (SSM) of theoretical events. When comparing independent observed and theoretical catalogues, average error of prediction of the time parameter for large and intermediate earthquakes (M > 5.5-5.8) was estimated as 1 year (Table 2). Average error of prediction of location is about 20 km. Therefore, the values of seismic moments were calculated, within volume of crust with dimension 0.4 degrees x 0.4 degrees in plane and 40 km in depth, for all theoretical events that may occur during time period of 2 years. The well-known relation between moment magnitude M_W and seismic moment M_0 was used, namely: $M_W = 2/3 \log_{10} M_0 - 10.7$. Figure 7 shows distribution of SSM values (base 10 logarithm) along the territory for shallow events (depth 0-40) and location of large (M > 5.9) real earthquakes. All real large earthquakes did occur within the areas with increased SSM values: $\log_{10}$ SSM > 25 corresponds to earthquakes with $M_W > 6.0$. Using the schemes compiled for the nearest future, one can make suggestion about development of seismic process in the region. On the other hand, the schemes calculated for various consecutive periods of time may be used as a basis for time-dependent hazard assessment.

GROUND MOTION MODELS

Forecasting of ground shaking is one of the crucial points in earthquake hazard assessment and loss estimation. The quantitative (peak amplitudes, response spectra, time histories of the motion, etc.) measures of ground shaking are widely used in aseismic design. The existing loss models, besides the quantitative parameters, are also based on qualitative (e.g. seismic intensity) measures. Estimation of the parameters includes several sources of uncertainty, which are attributed to earthquake occurrence, lack of knowledge of parameters of earthquake sources, attenuation of seismic radiation, and local soil amplification. The tool for reducing uncertainty in earthquake source characteristics (location, magnitude and occurrence) has been discussed in previous section. Uncertainty in ground motion modeling may be reduced, on the one hand, by using additional data and by developing of comprehensive models. However in many regions there is a lack of such models. The choice is restricted by a limited number of attenuation relations, which were developed for a few regions and generalized site conditions. Direct conversion one parameter to another, for example, PGA values to intensity, may lead to erroneous estimations, because seismic intensity, besides the amplitude, is a function of the duration and frequency content of ground motion.

In our approach we suggest to use Fourier amplitude spectrum of ground acceleration (FAS) as a universal input parameter in seismic hazard analysis, both deterministic and probabilistic ones (Figure 8). The advantages of using FAS are as follows.

1. Various regional source scaling models and attenuation relations based on empirical data have already been developed, or may be easily established for the region under study. It seems to be possible to estimate the spectral model for condition of rock sites, even if there is no rock reference station available (Sokolov [15, 16]. The spectral models, which were developed using database from small and moderate earthquakes (M < 6.5), allow constructing the reliable spectra for the case of larger (up to M = 7.5) events in the region (Sokolov [17]). Estimations of peak ground acceleration and response spectra may be obtained from FAS using stochastic technique (Boore [18]; Sokolov [19])

2. The variety of local soil conditions may be considered using soil/reference site spectral ratios. In this case, it is possible to use different site amplification functions, which depend on earthquake magnitude and distance, and to consider non-linear behavior of the soil during strong excitation.

3. The term “site & region & return period - specific strong ground motion parameters” also includes seismic intensity as a useful and simple quantity describing the damage due to earthquakes. The

technique, which is based of the recently established relationships between intensity and the Fourier amplitude spectra (Chernov [20], Sokolov [21]), allows evaluating absolute values of intensity directly using the site-dependent spectra.

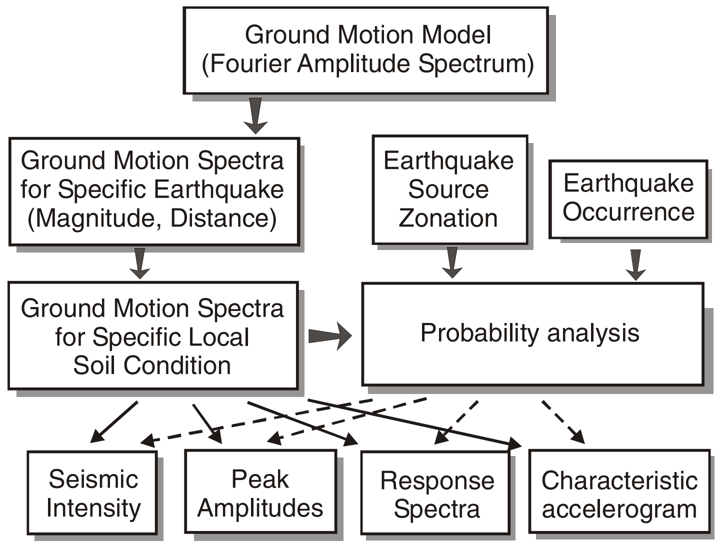

Figure 8. Seismic hazard assessment that is based on Fourier Amplitude spectra.

For the considered case we developed empirical models of ground motion spectra (very hard rock conditions, VHR) on the basis of records from recent (1993-1999) earthquakes. The database includes strong-motion data collected during the recent Chi-Chi earthquake (M=7.6, 21 September 1999) and large (M=6.8) aftershocks (Sokolov [17]). The ground-motion database was also used for evaluation of generalized site amplification functions for typical soil classes B, C and D (Sokolov [16]). Characteristics of site amplification were evaluated as the ratio between Fourier amplitude spectra of recorded accelerograms and spectra modeled for very hard rock (VHR). The amplification functions demonstrated their reliability when comparing with independent data. Description of soil classes B, C, and D may be found in Lee [22]. Figure 9 shows VHR spectra calculated for various magnitudes and generalized site amplification functions, which may be used jointly with VHR spectra for site-dependent analyses.

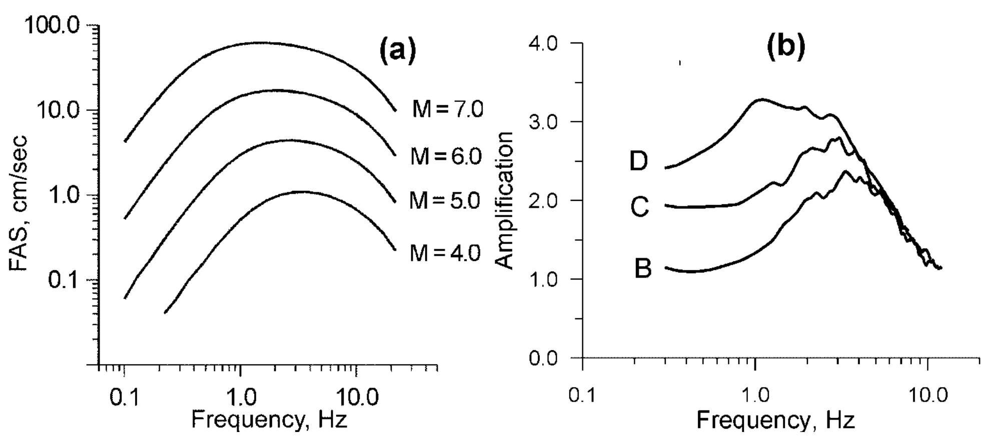

Figure 9. Ground motion characteristics for the Taiwan region. (a) Very hard rock Fourier amplitude spectra for hypocentral distance 10 km. (b) Generalized empirical site amplification functions for various site conditions (B, C and D).

TIME-DEPENDENT HAZARD FOR THE TAIWAN REGION

The region & site & time-dependent seismic analysis is based on schemes of probable earthquake zones (Figure 7), regional source scaling and attenuation models (Figure 9a), and information on local site response on seismic motion (Figure 9b). The following scheme was applied. First, for consecutive time periods T of 2 years the maximum magnitude M of characteristic earthquake was evaluated for all elementary volumes (I, J) of crust (0.4 degrees x 0.4 degrees in plane and 0-40 km in depth) within the considered region on the basis of values of summarized seismic moment of all theoretical events that may occur within the volume (see Figure 7, as example). The characteristic earthquakes were used for calculation of ground motion parameters along Taiwan Island. The uncertainty in location, geometry and dimensions of future earthquake sources. The uncertainty was considered as follows: five points inside the elementary volume were accepted, with equal probability, as location of the characteristic events. Two values of characteristic depth (5 km and 15 km) were used. The source-to-site distances R, ten values for every site and elementary volume, were evaluated using these parameters of the source location.

Ground motion parameters (Peak Ground Acceleration and Response Spectra at selected frequencies), which may be expected during future earthquakes, were evaluated for grid points (10 km x 10 km) covered Taiwan Island. For every grid point (i, j) the probability that ground motion parameter X will not exceed a given value x may be estimated as follows:

$$P_{(M=m;R=r;t=T)}\left[X \leq x\right] = \frac{1}{\sigma_x\sqrt{2\pi}} \int_{x\min}^{x} \exp\{(x-a)^2 / 2\sigma_x^2\}\, dx \qquad (1)$$

where a is the mean value of $\log_{10} X$ for an earthquake of given M (magnitude) and R (distance) that will occur within elementary volume (I, J) during time period T; σ_x is standard deviation describing the scatter of ground motion parameter for the earthquake, and $x_{\min}$ is of sufficiently small value ($x_{\min} \approx a$ - 5 σ_x). As far as we have ten values of characteristic distance, the resulting function P was calculated as an average of the particular functions $P_{R=Ri}$.

Peak Ground Acceleration (PGA) values and Response Spectra amplitudes (RSA) at selected frequencies (parameter a in equation 1) were calculated on the basis of regional spectral models (FAS) and generalized site response functions using stochastic approach. A set of 40 synthetic acceleration time functions was generated for every M-R pair using effective duration (regional estimations). The resulting parameters (PGA and RSA) were estimated as the average values calculated from the set.

The cumulative probability functions P for the single grid point (observation site) were calculated from all M-R pairs (elementary volumes I, J). The values of ground motion parameters were determined for three values of probability, namely: 0.5 (mean value), or 50% of being exceeded during the given (M, R) event; 0.84 (mean + 1 standard deviation), or 16% of being exceeded; 0.97 (mean + 2 standard deviation), or 3% of being exceeded. The maximum value of ground motion parameter resulting from all considered (M, R) pairs was finally assigned to the site.

The approach may be considered as a modification of so-called “scenario earthquake” analysis, or as a variant of “logic tree” approach. In this case we did not consider the distribution of earthquakes in time in a probabilistic manner. We introduce “the time dependency” by calculation of the ground motion parameters distribution for the certain periods of time T (2 years). In this study we determined maximum value of ground motion parameter for a point of the grid (i, j) using all considered time periods (2003-2025). It is possible to apply various weights for various time periods that should reflect the increasing uncertainty of earthquake prediction in the course of time. However, in this study we apply similar weights for all considered time periods.

Figure 10 presents, as an example, the seismic hazard zonation maps in terms of Peak Ground Acceleration (the contours are given in cm/s^2). The schemes show distribution of amplitudes that will not be exceeded with 84% probability in condition of generalized soil classes during all possible earthquakes that may occur in the region during time period of 2003-2025. The other ground motion parameters, such as response spectra or seismic intensity, may be also easily estimated using the proposed approach. We should note that all characteristic earthquakes in this study were considered as point sources, even with five possible locations, therefore the contours are characterized by a concentricity. The 3D representation the source (length, width, strike and deep characteristics) is more reliable. However, in this case a study of predominant source parameters in the Taiwan region should precede the ground motion calculations. This is one of topics of future research.

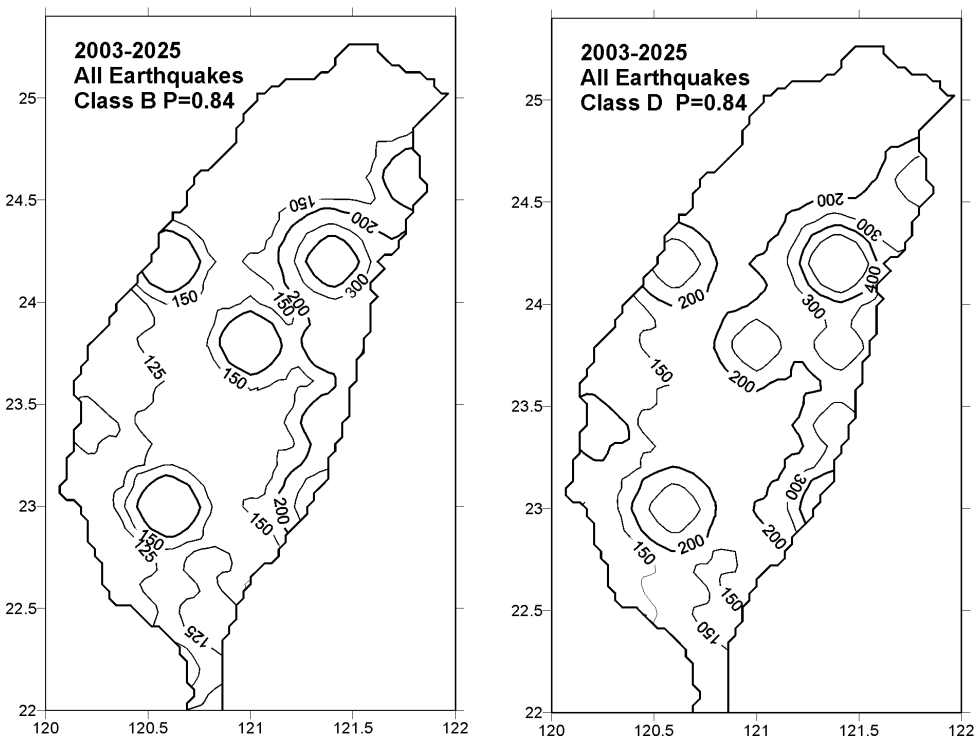

Figure 10. Distribution of Peak Ground Acceleration values (cm/s^2), which will not be exceeded with probability *P* (84%) in conditions of generalized soil classes (B and D) during time period of 2003-2025.

The approach used in the study allows us to introduce a new parameter that describes dependency of seismic hazard on time, so-called "*period of maximum hazard*" or PMH (Figure 11), which is of particular interest of seismic risk management and insurance business. As far as we have several schemes of seismic zonation (source zones) for various time periods, it is possible to evaluate the period, during which every considered site will experience the *maximum value* of ground motion parameter. When using jointly, the three types of zonation maps (future seismic source zones [Figure 7], distribution of ground motion parameters [Figure 10], and period of maximum hazard [Figure 11]) allow optimization of engineering decisions, and may be considered as a basis of seismic code development.

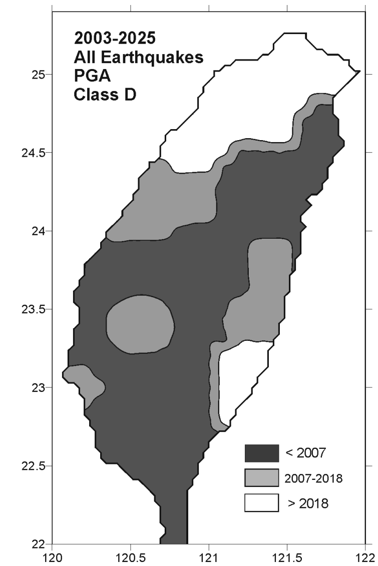

Figure 11. Distribution of "period of maximum hazard" (PMH) – the parameter that describes dependency of seismic hazard on time. PMH denote the period, during which every considered site will be subjected by the maximum value of considered ground motion parameter (PGA in this case).

CONCLUSION

The described researches may be considered as the parts of unified approach to region & site & time-dependent seismic hazard assessments, namely: from evaluation of characteristics of future earthquakes to ground motion parameters, which are used in seismic design and risk management.

The theoretical seismic catalogue of future earthquakes is calculated using the numerical modeling of the Earth' crust dynamic deformation (4D-model) and seismicity (5D-model). The developed models adequately describe the observed seismicity in the studied region. The theoretical catalogue is used as a basis for future earthquake zonation and determination of maximum-magnitude earthquakes for various time periods and various locations. When evaluating ground shaking parameters for purposes of seismic hazard and seismic risk assessment, we suggest using Fourier amplitude spectrum of ground acceleration (FAS) as a universal input parameter in seismic hazard analysis. For the case of Taiwan region, we developed empirical models of ground motion spectra on the basis of several thousands records from recent (1993-1999) earthquakes. The schemes of probable (future) earthquake source zones, regional source scaling and attenuation models, and information of local site response are used for region & site & time-dependent seismic hazard analysis. The approach allows us to introduce a new parameter that describes dependency of seismic hazard on time, so-called "period of maximum hazard" or PMH, which is of particular interest of seismic risk management and insurance business.

We should note that the results obtained in this study (Seismic Hazard Zonation) should be considered as preliminary variant. Bearing in mind several shortcomings and unresolved problems, the described approach should be developed further, both in general and particular aspects.

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