

Evaluation of parameters of future earthquakes for purposes of seismic hazard assessment

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ABSTRACT: The method for evaluation of seismic hazard, which is based on models of dynamic deformation of the Earth' crust, is described. The 4D-model (geographic coordinates, depth, and time) of deformation is constructed on the basis of observed geophysical data: GPS network, Sea Water Level monitoring, seismic catalogues, and other data reflecting dynamic process of the deformation. The process is considered as interaction of slow-propagating waves (fronts) of deformation, the moving velocities of which vary between 0.05-300 km per year and effective widths are about several tens of kilometres. The possible earthquakes could be revealed by analysis of distribution of deformation inside the crust. The case of recent 1999 Chi-Chi, Taiwan, earthquake of $M=7.6$ is described as an example. On the other hand, the seismic events are considered as the peculiar points of dynamic deformation – the moments of interaction of four and more fronts of deformation. Earthquake magnitude is evaluated using statistical 5D-model (geographic coordinates, depth, time, magnitude). The 4D/5D-models are applied jointly for compilation of theoretical seismic catalogue for the nearest tens years that is used for purposes of seismic zonation. The results of the modelling are described for the case of Taiwan region. Theoretical catalogue is compared with observed data.

1 INTRODUCTION

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 coordinate measurement (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. When analyzing the process of deformation, it is necessary to utilise all kinds of the direct and indirect data that would allow modelling the process in a given volume of the crust.

The general approach for development of the 4D (x, y, z, t – coordinates, depth and time) models of geological and geophysical processes is as follows. A function $F [\mathbf{p}, x, y, z, t]$ is introduced on the basis of available data. The vector \mathbf{p} describes parameters of the process. The most of these parameters, as well as the type of the function F , are not initially known. It is supposed that the

function F reflects the considered geological phenomenon adequately. The problem consists in a search of the vector p on the basis of uncompleted observational data $\{F_i, i = 1, n\}$. When determining the function F , we assume, as a basic principle, that the Earth's crust contains the slow-propagating waves (fronts) of tectonic deformation. The presence of these deformational (stress) waves was suggested by many authors (e.g. Elsasser 1969).

From the seismological point of view, the main goal of modelling of the process of dynamic deformation is to compile a complete 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. When constructing the models, it is necessary to use analytical approximation. Two such approximations (4D and 5D) have been proposed (Ovcharenko 1999; Ovcharenko et al. 2001). The models were applied for calculation of theoretical catalogue for future 40-50 years for Taiwan region (119-123 E, 21-26 N). The observed data including regional seismic catalogue (115-125 E, 15-35 N; depth 0-200 km; period of observation 1900-2001.5 (June, 2001)) were used as input data. The parameters of observed earthquakes and theoretical events for time period between July 2001 and May 2002 are compared to test the efficiency of prediction.

2 DESCRIPTION OF THE MODELS

The data that reflect the dynamic process of the Earth crust deformation may be divided into two types, namely: direct and indirect data. The direct data are obtained during GPS (Global Positioning System) monitoring, instrumental observation of stress and deformation in mines, and geodetic observation. Observation of gravitational, magnetic and electromagnetic fields, elastic properties of geological medium, water level in boreholes, changes of the coastline, and volcanic activity may be considered as the indirect data. The indirect data are frequently characterised by the cheapest, longest and high-quality time series. The seismic events should be considered as an important indicator of stress-strain state of the Earth crust, because earthquakes are result of complicated process of deformation and fracture of the crust. However, the indirect data provide information only about the dynamics of the process. The amplitude of deformation should be determined on the basis of direct data. The comprehensive mathematical description of the models was given in (Ovcharenko 1997, 1999; Ovcharenko et al. 2001). In this paper we show only the basic and simplest equations.

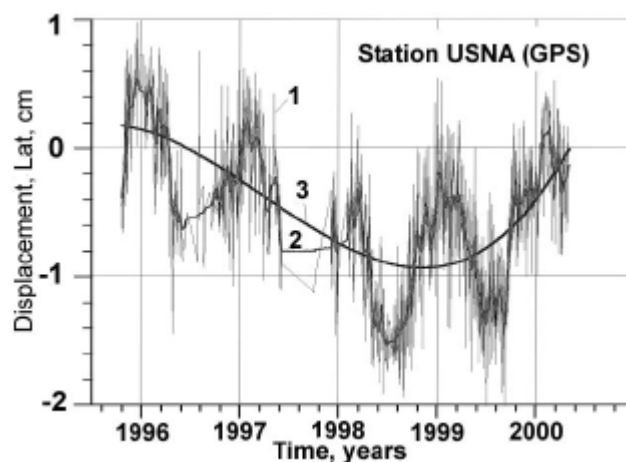


Figure 1. Dynamic nature of the Earth crust deformation. Typical waves of deformational that could be revealed from the GPS data (station USNA, Lat. 38.98N, Lon. 76.48 W). 1 – observed latitudinal displacements; 2 – curve, which obtained after smoothing (14-points running average), reveals five fast-propagating fronts of (probably) seasonal nature; 3 – third-power polynomial shows a slow-propagating front of deformation.

2.1 4D-model of dynamic deformation

The simplest variants of the 4D-model may be constructed using a system of plane fronts (waves) of

deformation (FD) with uniform propagation (e.g. Ovcharenko 1997, 1999). The idea is supported by results of theoretical studies of deformation of elastic media. Experimental data also allow revealing of slow-propagating non-periodic impulses of deformation in the Earth crust (Fig. 1). The function of elastic deformational displacement for a set of plane FDs in infinite medium may be determined as

$$E(x, y, z, t) = \sum_{i=1}^n m_i \frac{1}{q_i} \quad (1)$$

$$\left. \begin{aligned} q_i &= (p_i^2 + \mathbf{e}) \\ p_i &= (y - a_i x - b_i z - c_i t - d_i) \end{aligned} \right\} \quad (2)$$

where (x, y, z, t) are the Cartesian coordinates and time; (a, b, c, d) are the kinematical parameters of the model; $2\mathbf{e}$ is the effective width of the FD; m_i are the amplitude (energy) characteristics of the model; n is the number of FDs. The components of deformation for a set of the FDs, components of velocity of deformation, and inclination of daily surface may be determined from these basic equations.

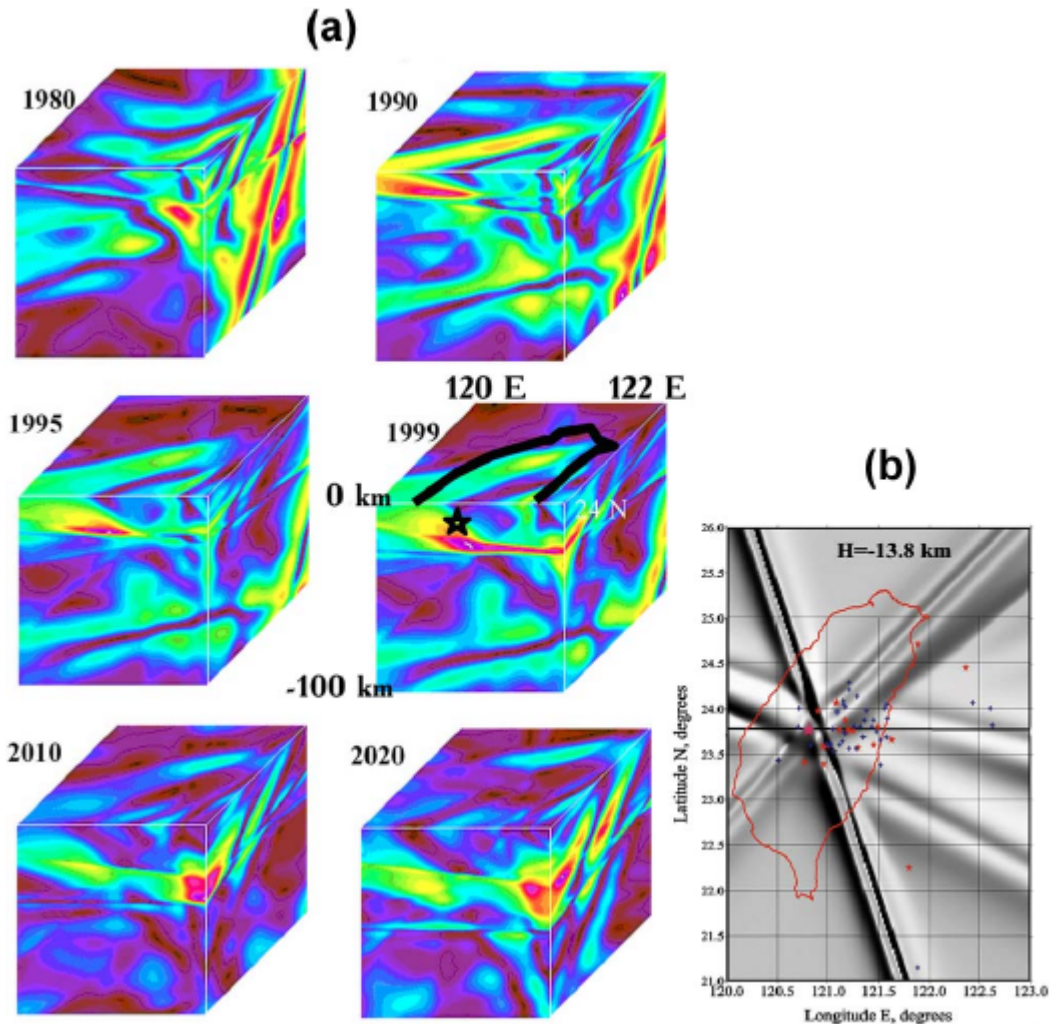


Figure 2. Example of application of the preliminary 4D-model for the northern part of Taiwan Island. a) Absolute vector of deformation; violet and blue areas correspond to the zones of tensional deformation, yellow and red areas denote the compression zones. The epicentre of the Chi-Chi earthquake (1999, reverse faulting) is shown by black star. b) The fronts of dynamic deformation (FDD) which were modelled for September 1999, depth 13.8 km. Big star – the Chi-Chi earthquake hypocenter; small stars denote earthquakes occurred before the Chi-Chi earthquake; crosses show earthquakes occurred after the Chi-Chi earthquake mainshock.

The dynamic model for a set of the FDs may be constructed using various kinds of observed data by solution of the *inverse* task. The goal of the task is determination of parameters $\{a_i, b_i, c_i, d_i, m_i, i = 1, n\}$ which satisfy the experimental data. It is proposed to decompose the initial task into two parts. The first part, or *inverse kinematical* task, consists in determination of kinematical parameters of the model $\{a_i, b_i, c_i, d_i, i = 1, n\}$. The indirect data, describing the dynamic nature of the process, may be used only for solution of the inverse kinematical task. The second part, or *inverse dynamic* task, consists in determination of amplitude parameters of the model $\{m_i, i = 1, n\}$ using the data that were obtained during the direct observation of the Earth's crust deformation (GPS, geodetic measurements, etc). The corresponding problem can be solved using the Tikhonov's smoothing function

$$M^{\alpha} [E, K, m] = \sum_{j=1}^k (E_j - \sum_{i=1}^n m_i K_{ij})^2 + \alpha \sum_{i=1}^n (m_i)^2, \quad (3)$$

where $?_j(x, y, z, t)$ are the components of deformation observed at stations $\{x_j, y_j, z_j, t_j\}, j = \overline{1, k}$; $m_i, (i = \overline{1, n})$ are the unknown parameters of the model; α is the parameter of regularization; K is the kernel function that depends on the observed parameter of deformation. The solution of the similar tasks in geophysics has been thoroughly investigated and widely applied (Tikhonov & Arsenin 1979).

The possible seismic events, on the one hand, could be revealed by analysis of distribution of deformation inside the Earth' crust. Figure 2 shows the results of application of the preliminary 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, see also Shin & Teng, 2001). The data include GPS (e.g. Yu et al. 1997) and PSWL observation, and seismic catalogue (National Weather Bureau). The development of a narrow zone of intensive compression (depth about 10-20 km) in the central part of Taiwan Island is clearly seen (Fig. 2a). 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. On the other hand, it is proposed to consider seismic events as the peculiar points of the field of dynamic deformation – the moments of interaction of four or more fronts of dynamic deformation (FDD). The location of the Chi-Chi earthquake source is clearly fixed by the correspondent zone of interaction of several revealed FDDs (Fig. 2b).

2.1 5D-model of seismicity

The 4D-model, as a model of deformation that causes the rupture processes inside the crust, uses the phenomena of rupture (earthquakes) as a geodynamic indicator of deformation. 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 (coordinates, depth, and time) of an idealised 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. The volume is characterised by complex distribution of deformation and stress and development of earthquake rupture depends on mechanical and chemical processes in the crust. Therefore, it is not possible to establish a simple correlation between earthquake energy (magnitude) and parameters of deformation determined by the 4D-model. 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 idealised point of the FDDs interaction. These factors lead to the uncertainties in magnitude, time and coordinates of potential seismic events predicted by the considered deformational model.

On the other hand, it is naturally to assume that “background” seismicity reflects the above mentioned parameters of the Earth' crust in the given region. Therefore, a statistical formalised 5D (x, y, z, t, M - coordinates, depth, time, magnitude) model of seismic process, which is based only on seismic data, has been developed. The seismic catalogue may be considered as a 5D table. Every event from a general set should belong to at least five subsets with the linear relations between coordinates and time. For a single statistical subset, the following generalised equation may be written

$$M = aX + bY + cZ + dT + e \quad (4)$$

where (a, b, c, d, e) are the unknown parameters, and (x, y, z, t, M) are the parameters of seismic event

in catalogue. The algorithm of determination of the parameters $\{a_k, b_k, c_k, d_k, e_k, k = \overline{1, n}\}$ represents the essence of approximation of seismic catalogue, or the concept of the 5D model (Ovcharenko et al. 2001). All seismic events in the catalogue are described by at least five relationships.

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. First, the 5D-model is applied to find a potential event (x, y, z, t, M) . Second, the revealed event (x, y, z, t, M) is tested to evaluate whether the correspondent point exists in the 4D-model. The testing is performed by analysis of all fronts of dynamic deformation (FDD) and by calculation of the criterion

$$Y - |aX + bZ + gT + I| \leq e \quad (5)$$

where (a, b, g, I) are the kinematical parameters of the FDDs; e is the model accuracy. The point belongs to the 4D-model if the criterion is fulfilled for at least five FDDs. Magnitude of the prognostic event is evaluated by the 5D-model. A scheme of the process is shown in Figure 3. Note, that only seismological data are used in the 5D-model.

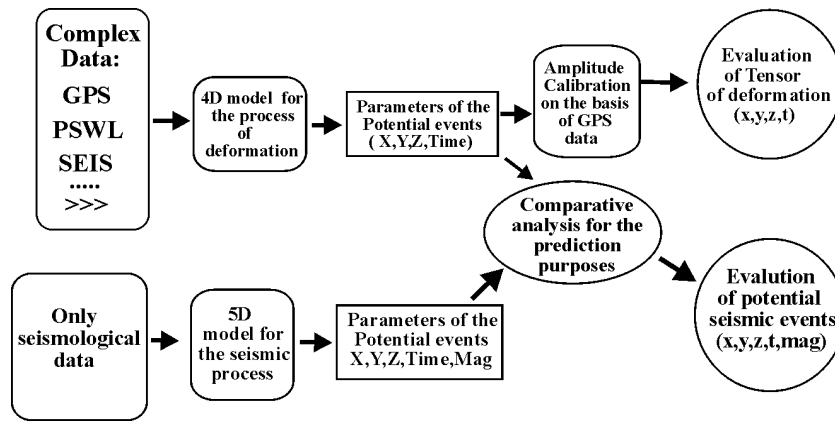


Figure 3. Scheme of the forecasting process using the 4D- and 5D-models.

3 RESULTS OF THE MODELS APPLICATION

The models were developed for the Tawan region on the basis of seismic catalogue (more than 190,000 events) for the time period before the Chi-Chi earthquake (1900-1999.683). First, the models were used for calculation of theoretical catalogue that corresponds (approximates) to the observed one. When comparing the theoretical and observed catalogues, it has been found that the main part (95 %) of the theoretical catalogue is characterized by small errors of approximation. Standard deviation reflecting the difference between parameters of observed earthquake and corresponding theoretical event is as follows: 14 km and 11 km for latitude and longitude; 4.5 km for depth; 2.1 years for time of occurrence; 0.12 unit for magnitude (Fig. 4a).

The algorithm was also tested using control series containing independent set of observations, namely: standard catalogues issued by Central Weather Bureau, Taiwan, which were obtained after the Chi-Chi earthquake during the time period of 1999.85-2000.8. The control series contains about 700 events with magnitudes $3 < M < 6.2$. The modelling of the seismic process allowed obtaining statistically reliable results. The errors (standard deviation) of correspondence between theoretical and real earthquakes are as follows: 32 km and 27 km for latitude and longitude; 2.0 km for depth; 0.11 units for magnitude. The time parameter, or the moment of earthquake occurrence, is characterized by the largest error (standard deviation about 9 years) that relates to small ($M < 4.0$) events. On the one hand, for the purposes of seismic zonation, even the relatively large errors of the moment of earthquake occurrence are admissible. On the other hand, the control series included the aftershocks of the Chi-Chi earthquake, which in the frame of the used dynamic model may be considered as earthquakes triggered by the mainshock.

Figure 4b compares 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. 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, causes new events due to interaction with the existing FDDs. Therefore, the aftershocks may be divided, at least, into two groups, namely: “triggered” events that are caused by the additional post-earthquake front and “independent” earthquakes resulted from interaction of the existing FDDs.

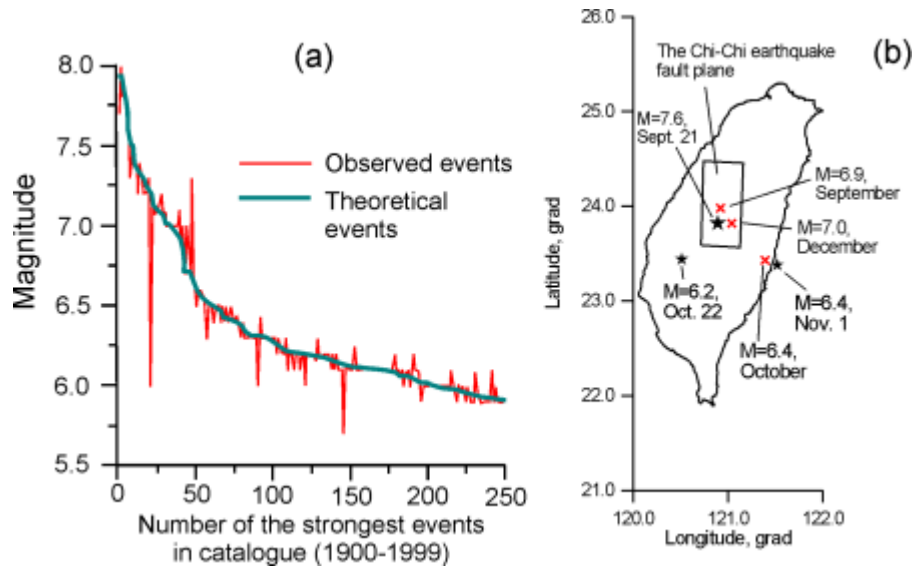


Figure 4. Comparison of observed and theoretical seismic catalogue.

a) Evaluation of accuracy of approximation (magnitude) of the real seismic catalogue (Taiwan region, 1900-1999) by the modelling. 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).

The prognostic theoretical catalogue for the Taiwan region (119-123 E, 21-26 N) has been calculated up to 2050 starting from July 2001 (2001.5). When the paper being prepared, there was a possibility to compare parameters of observed earthquakes and theoretical events for time period between July 2001 and May 2002. Bearing in mind the possible error in evaluation of the time parameter (date of earthquake occurrence), the direct comparison between observed and theoretical catalogues is shown (Fig. 5a) for the following time periods: observed earthquakes – July 2000-May 2002 (818 events with $M > 3.5$); theoretical events – January 2001-December 2002 (829 events with $M > 4.0$). There is, in general, a good agreement between grouping (clusters) of observed earthquakes and theoretical events in the central part of Taiwan and eastern coastal areas. The discrepancies are observed for the remote boundary zones where the necessary observational (input) data are insufficient and even absent.

When comparing large theoretical seismic catalogue and observed seismicity, it necessary to resolve the problem: how it is possible to identify two correspondent events in 5D-space (geographic coordinates, depth, time and magnitude)? The following simple approach was used. Let us denote the parameters of event as follows: longitude as X_1 , latitude as X_2 , depth as X_3 , time as X_4 , and magnitude as X_5 . During the first step, all parameters of the catalogues are normalized and centred as

$$x = (x - x_0) / s_x, \quad s_x = \sqrt{(x - x_0)^2 / n}, \quad x_0 = (\sum_{i=1}^n x_i) / n \quad (6)$$

The “distance” d (or a quantity related to correspondence of the events) between two events is evaluated as follows

$$d(x_F, x_P) = \sqrt{\sum_{i=1}^5 (x_{iF} - x_{iP})^2 / 5} \quad (7)$$

where x_F is the arbitrary earthquake in the observed catalogue, and x_P is the event from theoretical catalogue. Thus, when evaluating the error of prognosis, we should determine “the best prognostic” events as the event with the lowest value of d . Obviously, different weights (influence on the choice) may be applied for the parameters of earthquakes (coordinates, depth, time, and magnitude) in order to increase or decrease influence of a specific parameter. Comparison of parameters of observed earthquakes (magnitudes more than 5.0) and correspondent (“best prognostic”) events in theoretical catalogue shows that the absolute difference does not exceed 0.1-0.15 degree for coordinates, 10 km for depth, 1.1 year for time of occurrence and 0.1 unit for magnitude. Figure 5b compares location of epicentres of large ($M > 5.9$) earthquakes occurred in the region during the considered period and the correspondent events in theoretical catalogue. For all pairs (observed-theoretical earthquakes) the difference between coordinates does not exceed 0.3-0.4 degrees (30-40 km). Obviously, the prediction should be considered as successful, if the difference between hypocenter of observed earthquake and location of theoretical seismic event does not exceed largest dimension of the earthquake source (40-50 km for earthquakes of $M > 6.0$).

It seems to be more useful to consider distribution of summarized seismic moments (SSM) of theoretical events rather than a single large earthquake. Figure 6 shows distribution of SSM values (base 10 logarithm) along the territory for shallow events (depth 0-40 km) and location of large ($M > 5.9$) real earthquakes. 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 (\pm absolute error of approximation). All real large earthquakes occurred within the areas with high SSM values: $\log_{10} \text{SSM} > 25$ corresponds to earthquakes with $M_W > 6.0$. However, there are zones with relatively high SSM values where large earthquake did not occur till the moment of the paper preparation (July 2002).

As far as the theoretical seismic catalogue allows constructing of several schemes of SSM distribution (seismic zonation) for various time periods in future, they may be considered as a basis for “time-dependent” seismic hazard analysis. On the other hand, the models should be re-evaluated after every large earthquake and when accumulating new experimental data (2-3 years). Besides estimation of the time, location and magnitude of *future* events, there is also a possibility to evaluate parameters of *historical* earthquakes, which is very important problem for the seismic hazard estimation. The models, in essence, are not region-dependent. It is possible to test their reliability by application in other seismic regions that are characterized by different tectonic settings and seismicity.

REFERENCES:

- Elsasser, W.M. 1969. Convection and stress propagation in the upper mantle. In S.K. Runcorn (ed.), *The Application of Modern Physics to the Earth and Planetary Interiors*, 223-246.
- Ovcharenko, A.V. 1997. Estimation of the velocity of modern horizontal displacement of the Urals Earth crust from vertical movement and relief of the day surface, *J. of Earthquake Prediction Research*, 6(4), 510-526.
- Ovcharenko, A.V. 1999. 4-Dimensional models of deformation of the Earth's crust and earthquake prediction, *J. of Earthquake Research in China*, 13(1), 60-84.
- Ovcharenko, A.V., Sokolov, V.Yu., Loh C.-H. & Wen K.-L., 2001. Analytic continuation of the seismological catalogue of the Taiwan region based on models of deformational and seismic processes of the Earth' crust, *Urals Geophysical Bulletin*, 2, 49-55 (in Russian).
- Shin, T.-C. & Teng T.-L., 2001. An overview of the 1999 Chi-Chi, Taiwan, earthquake, *Bull. Seism. Soc. Am.*, 91, 895-913.
- Yu, S.-B., Chen H.-Y. & Kuo. L.-C., 1997. Velocity field of GPS stations in the Taiwan area, *Tectonophysics*, 274, 41-59.

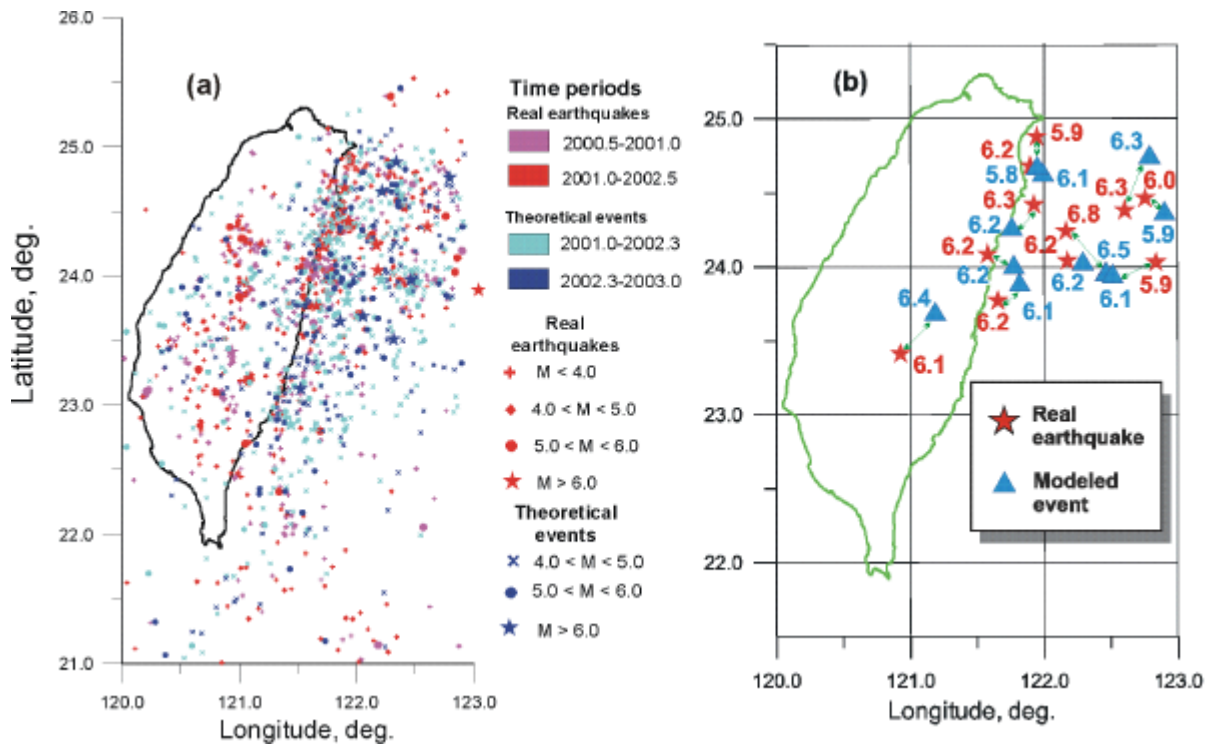


Figure 5. Comparison of location of observed earthquakes and events in the theoretical catalogue. a) All observed earthquakes ($M > 3.5$, July 2000-May 2002) and theoretical events ($M > 4.0$, January 2001-December 2002). b) Location of epicentres of real earthquakes with magnitudes > 5.9 and correspondent theoretical events.

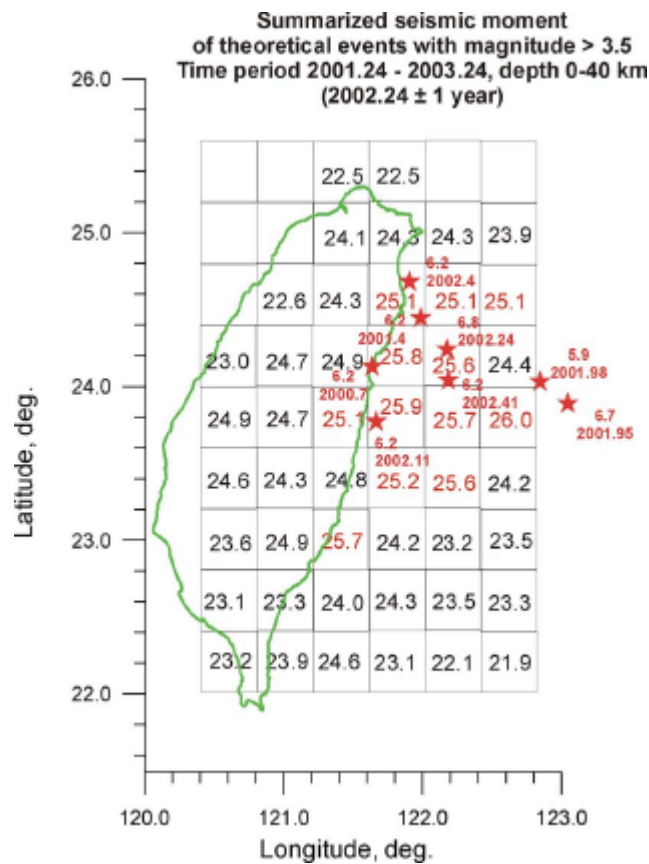


Figure 6. Distribution of summarized seismic moment values (base 10 logarithm) for shallow theoretical events (depth 0-40 km). Epicentres of large observed earthquakes, magnitude and date of occurrence are shown for comparison