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EARTHQUAKE DISASTER COUNTERMEASURES FOR SUBDUCTION ZONE EARTHQUAKES BASED ON STRONG GROUND MOTION AND TSUNAMI PREDICTION

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ABSTRACT: The Central Disaster Management Council (Chairman, the prime minister) is taking initiatives on planning basic schemes and promoting execution of disaster countermeasures in Japan. Recently, the council and the specialists committees, which are constituted under the council, carried out studies for the major subduction zone earthquakes along the Suruga and Nankai trough. The results are summarized and used for designation of the areas to strengthen and promote disaster management, damage estimation, and emergency response operations.

Key Words: disaster management, hazard mitigation, subduction zone earthquakes, strong ground motion, tsunami, prediction

INTRODUCTION

Japan has experienced many earthquake disasters and will face forthcoming earthquakes. Crustal earthquakes of magnitude 7 or larger are caused by active faults running inland. Subduction zone earthquakes larger than magnitude 8 occur along the Japan trench or along the Nankai trough, and magnitude of earthquakes in the Sea of Japan nearly reaches 8. Earthquake hazard mitigation and disaster countermeasures are urgent and important subjects for Japan.

Recently, a lot of data have been accumulated and various investigations have been done for strong ground motion effects on buildings and structures from recent earthquakes, especially from the 1995 Kobe earthquake and from the 2000 Tottori earthquake. The subsurface structures are intensively studied and many of geotechnical data have been accumulated in wide areas. Also, scientific investigations in recent years have gained understandings on earthquake occurrence mechanisms, earthquake source properties, and seismic wave propagation. The data accumulations and the developments on scientific investigations lead to another stage of the countermeasure planning based on more accurate estimation of hazards and disasters.

The Central Disaster Management Council is taking initiatives on planning basic schemes and promoting execution of hazard mitigation and disaster countermeasures in Japan. The Council has recently carried out studies on the Tokai earthquake and designated the areas to strengthen disaster management, and successively studied the Tonankai and the Nankai earthquake to designate the areas to promote disaster management. The council is presently investigating countermeasures for the earthquakes occurring directly below the metropolis, and also studying earthquake disaster management for earthquakes along the Chishima trench and the Japan trench.

In this paper, the approaches to disaster management for the Tokai earthquake and the Tonankai and Nankai earthquake are introduced.

HISTORICAL RECORDS

Past experiences of Japanese earthquakes were described on historical documents. Recently, studies of historical documents on earthquake effects and disasters have been developed. Magnitudes of historical events are estimated from documents on damages of houses, temples and shrines, and ground traces of tsunami. The historical documents provide a lot of lessons for the earthquake disaster countermeasures against forthcoming events, and they are especially useful for regions where earthquakes have been repeatedly occurring with almost identical source area, since they give us an idea of maximum magnitude in the area and provide data for calibration of strong ground motion and tsunami prediction.

In the Tokai, Tonankai, and Nankai areas, there were a number of historical events which repeatedly occurred in the same source regions. Since the 17th century, when the Tokugawa Shogunate was established, many historical records were uniformly available. There have been 6 major earthquakes recorded in historical documents, namely the 1605 Keicho earthquake (M7.9), the 1707 Hoei earthquake (M8.6), the 1854 Ansei Tokai earthquake (M8.4), the 1854 Ansei Nankai earthquake(M8.4), the 1944 Showa Tonankai earthquake(M7.9), and 1946 Showa Nankai earthquake(M8.0). The source area of the 1605 event and the 1707 event covered totally from the Tokai to Nankai area The first event in 1854 occurred in the Tokai and Tonankai area, and the second event in the same year occurred in the Nankai area. The 1944 event was limited in the Tonankai area, and the 1946 event in the Nankai area. These 6 events generated strong ground motions and great tsunami waves. There are a lot of records on damages due to strong ground motions and tsunami waves from these events.

We have reviewed literature and re-examined the descriptions on historical documents, in order to fully make use of the historical information. The maximum seismic intensity scales and maximum tsunami height ever experienced in these regions are shown in Fig. 1 and Fig. 2. Those are used for calibration of prediction of strong ground motion and tsunami height.

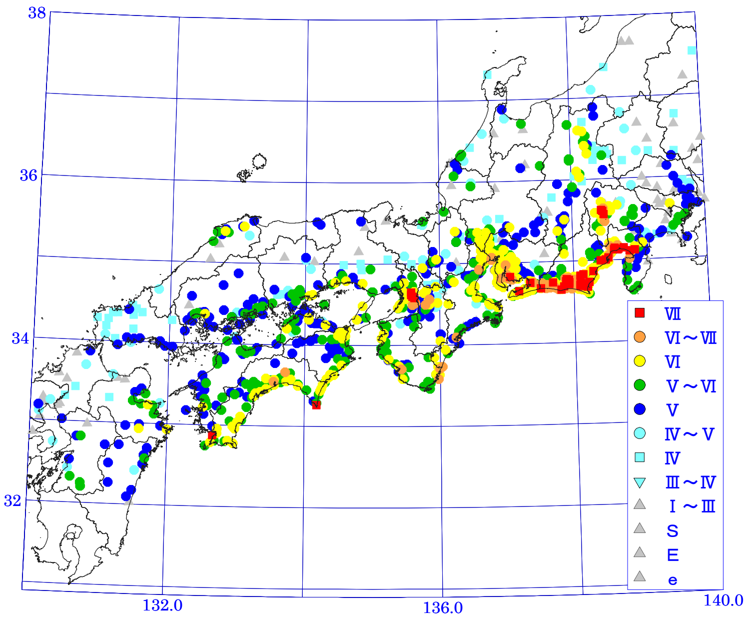

Fig. 1 The maximum intensity scale from 6 historical earthquakes in the studied area. JMA intensity scales are shown (JMA scale VI is equivalent to MM scale IX).

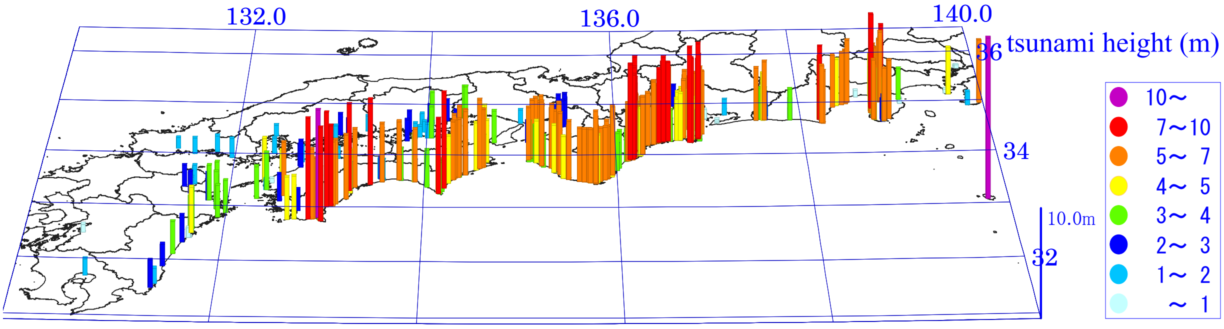

Fig. 2 The maximum tsunami height from 6 historical earthquakes in the studied area.

STRONG GROUND MOTION PREDICTION

Method of prediction

Prediction of strong ground motion is based on physical models of seismic source, seismic wave propagation, and surface layer effects on seismic waves. The JMA (Japan Meteorological Agency) intensity scale, maximum velocity, and maximum acceleration are estimated at each of about 46,000 meshes for the Tokai earthquake, and at about 170,000 meshes for the Tonanaki-Nankai earthquake. The mesh size is about 1,000m by 1,000m.

Simulations of strong ground motion are carried out by using Irikura's synthesis method (Irikura 1986) of stochastic Green's function (Boore 1983) from small elements on the source. The Green's function method assumes the far-field approximation of seismic radiation from the source. In applying the method to the near field strong ground motions, an analytical solution of simple crack problem is derived to modify the geometrical attenuation formulation so that the prediction is valid in the near field.

Shear waves propagate from each source element to the top of seismic base layer along ray paths of spherical earth model. We take into account the radiation pattern of seismic shear waves due to faulting, and SV and SH motions are separately radiated from the source. Linear effect of layers from seismic base layer to engineering base layer in a 3D structure model is calculated for each ray with corresponding incident angle from the source element. The SV and SH motions from all elements are synthesized and decomposed into two horizontal and vertical components at the top of engineering base layer. Non-linear effect of surface layers above engineering base layer is evaluated by assuming vertical incidence to one-dimensional stratified layers at each site.

Prediction of strong ground motion is not free from uncertainty. The results of prediction are compared with the observed data of historical events to verify their applicability to disaster management.

Seismic source models

Recent seismic source studies have revealed that source intensities are not uniform on the fault plane. Asperities are characterized as the regions where the slip displacement and stress drop are larger than in the surrounding area of the source. Asperities are also assumed to generate short period strong ground motions more effectively than the surroundings. Magnitudes of short period seismic radiations such as JMA intensity scale are thus controlled mainly by asperities on the fault. The ratio of asperity area to total fault area and that of asperity displacement to average fault displacement are studied (Sommerville et al. 1990). It is found that scaling relationship holds for microscopically for asperities as well as macroscopically for entire fault.

Location and intensity of asperities on the seismic sources of the Tokai, Tonankai, and Nankai earthquakes are determined based on the scaling relationship and according to the intensity scale distribution from historical records as shown in Fig. 1. The asperity distributions thus determined are shown in Fig. 3 and Fig. 4.

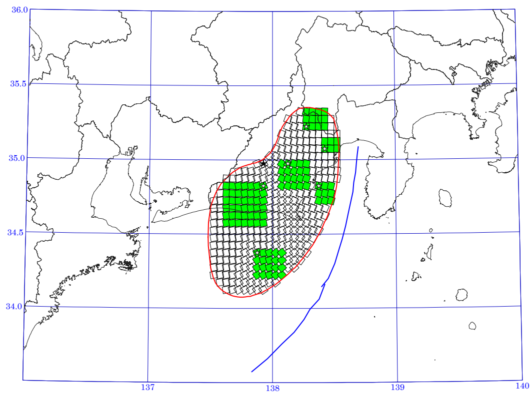

Fig. 3 Source area and asperities (green squares) of theTokai earthquake. Blue line is the Nankai trough.

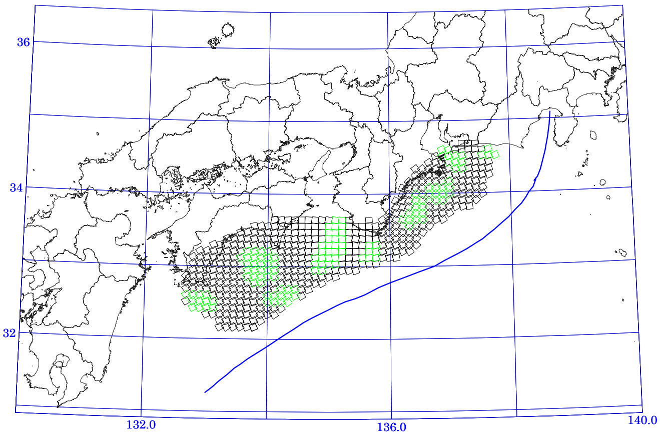

Fig.4 Source area and asperities (green squares) of the Tonankai and Nankai earthquakes. Blue line is the Nankai trough.

Subsurface structure

Subsurface structures above seismic base layer are modeled by using many data of geophysical exploration, boreholes, geology, and geomorphology.

Seismic base layer in the Tokai and Nankai area is found to be characterized by P wave velocity of about 5,500m/s and S wave velocity of about 3,000m/s, and the engineering base layer by S wave velocity of 700m/s. From seismic base layer to engineering base layer, the structure is approximately composed of three layers. The depth of each layer below the engineering base layer is determined at observation sites and three-dimensionally modeled by interpolation technique. Fig. 5 shows depths of the seismic base layer at the locations of geophysical exploration sites and boreholes. Fig. 6 shows the three-dimensional model of seismic base layer obtained by the present method.

Structure above engineering base layer is modeled at each mesh based on the PS logging and N value data of standard penetration test. The N values are used as estimates of S wave velocity from the relationship between them. The average S wave velocity from surface to 30m depth, or AVS30, is used as an index for surface structure characteristics. We have estimated the relationship between AVS30 and altitude, or distance from the river, for each of geomorphology classification. Fig. 7 shows the geomorphology class distribution in the area. The model structures are verified by the observed S wave spectra. Fig 8 compares the observed site spectrum with the calculated from the model structure.

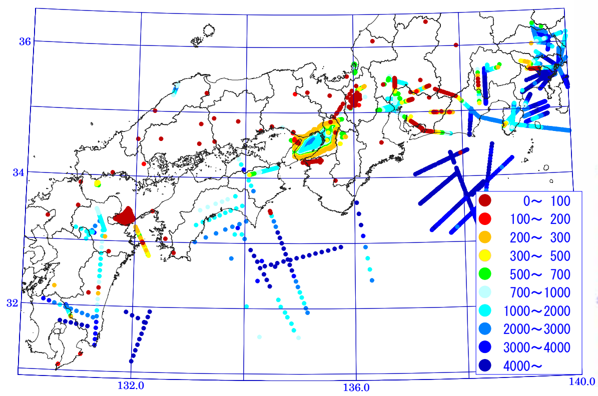

Fig. 5 Location of geophysical exploration sites and depths of top of seismic base layer.

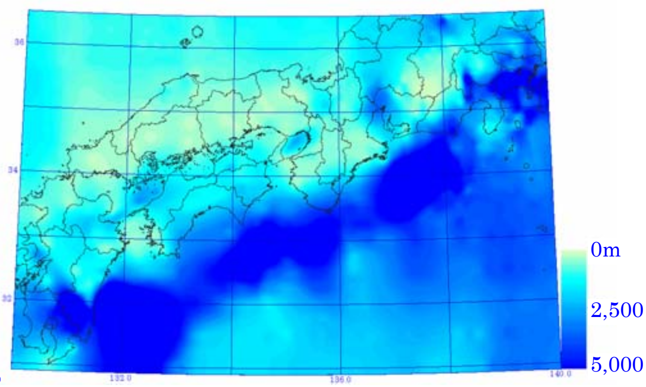

Fig. 6 Three-dimensional model of seismic base layer obtained here.

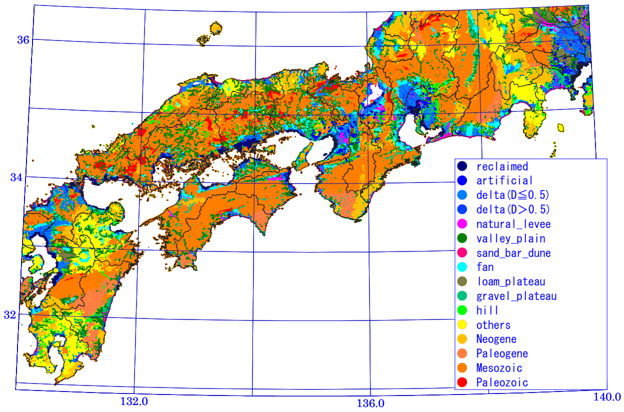

Fig. 7 Geomorphology classification in the area.

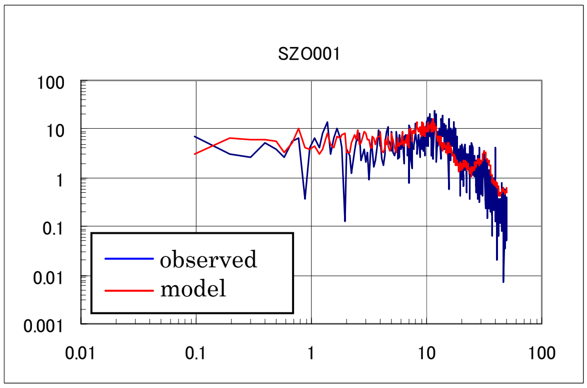

Fig. 8 Comparison of the model site spectrum to the observed.

Results of prediction

Fig. 9 and Fig. 10 show the JMA intensity scale distribution due to the Tokai earthquake of Mw 8.0, and due to the Tonankai-Nankai earthquake of Mw 8.6, respectively. The predicted distributions of JMA intensity scale are compared with and verified by historical distributions. The source area of the Tokai, Tonankai, and Nankai earthquake are close to the land, so that the JMA intensity scale of 6 to 7 is resulted along the coast near the asperities of the seismic source and at sites of soft surface layers.

The most remarkable feature of these earthquakes is that the affected area is extraordinary wide. Especially for the Tonankai-Nankai earthquake, the area of JMA intensity scale 6 is about 600km long ranging from Shizuoka Prefecture in the Tokai region to Oita Prefecture in the Kyushu Island, including large cities as Nagoya, Kyoto, and Osaka.

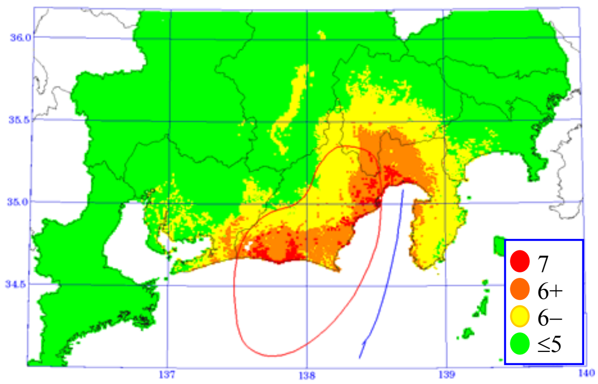

Fig. 9 JMA intensity scale due to the Tokai earthquake of Mw 8.0. Source area is shown by red line. Blue line is the Nankai trough.

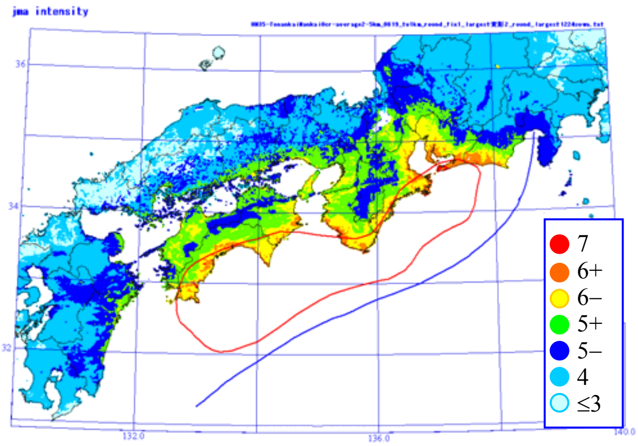

Fig.10 JMA intensity scale due to the Tonankai-Nankai earthquake of Mw 8.6. Source area is shown by red line. Blue line is the Nankai trough.

TSUNAMI HEIGHT PREDICTION

Method of prediction

As in predicting the strong ground motion, tsunami prediction is based on the physical models of tsunami source, tsunami wave propagation, and tsunami run-off into the land area. The tsunami height and tsunami travel time along the coast and water depth in land area are estimated for each of 50m meshes near the coast.

The crustal deformation due to earthquake faulting is calculated from the source model and the initial water level is given as the tsunami source. The equations of motion based on the long wave length theory are solved for tsunami propagation. Linear approximation is applied for deep ocean, and non-linear terms of mass transfer and friction are accounted for in shallow parts and inland areas. Simulations of tsunami propagation are carried out by the finite difference method.

Tsunami source models

The tsunami is generated by the uplift and subsidence of ocean bottom due to earthquake faulting, which is thus the controlling parameter. We set the slip distribution on the fault to the solution of inversion of the maximum tsunami height and crustal deformation data from historical records. The slip distribution obtained by inversion technique is shown in Fig.11.

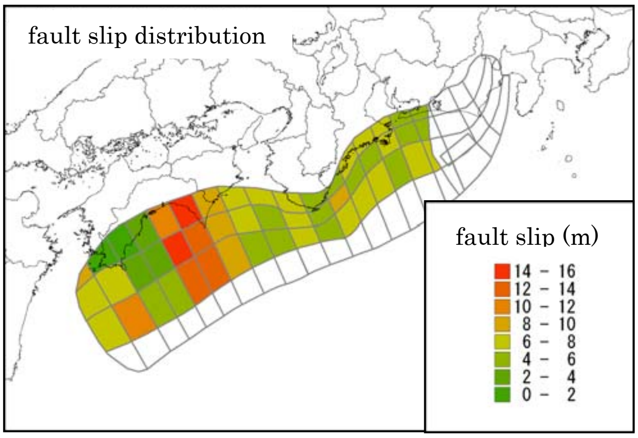

Fig. 11 Slip on the fault obtained by inversion.

Surface topography and other conditions

The ocean bottom topography and inland altitude are available from digital database. They are arranged as mesh models of various sizes of 1,350m, 450m, 150m, and 50m. Larger size mesh model is used for deep ocean and smaller mesh model is used for shallow water and inland area. The co-seismic crustal deformation is accounted for in measuring the water depth in land area. The two cases of average and maximum ocean tide level are considered. Main rivers are included and the geodetic data are used for the mesh model. Banks and coastal structures are put on the mesh boundaries. Manning's roughness coefficient is used to account for the friction at the water bottom.

Results of prediction

We calculated the tsunami height and tsunami run-off for the various occurrence types of the Tokai, Tonankai, and Nankai earthquakes. Fig. 12 and Fig.13 show the tsunami height and travel time due to the Tokai earthquake, and Fig. 14 and Fig.15 those due to the Tonankai-Nankai earthquake, respectively. The predicted tsunami height is compared with the historical data and verified by them. Fig. 16 compares the predicted tsunami height with the historical data. The coastal structures are not included in this case. It is shown that the tsunami source model obtained here well explains the historically observed data.

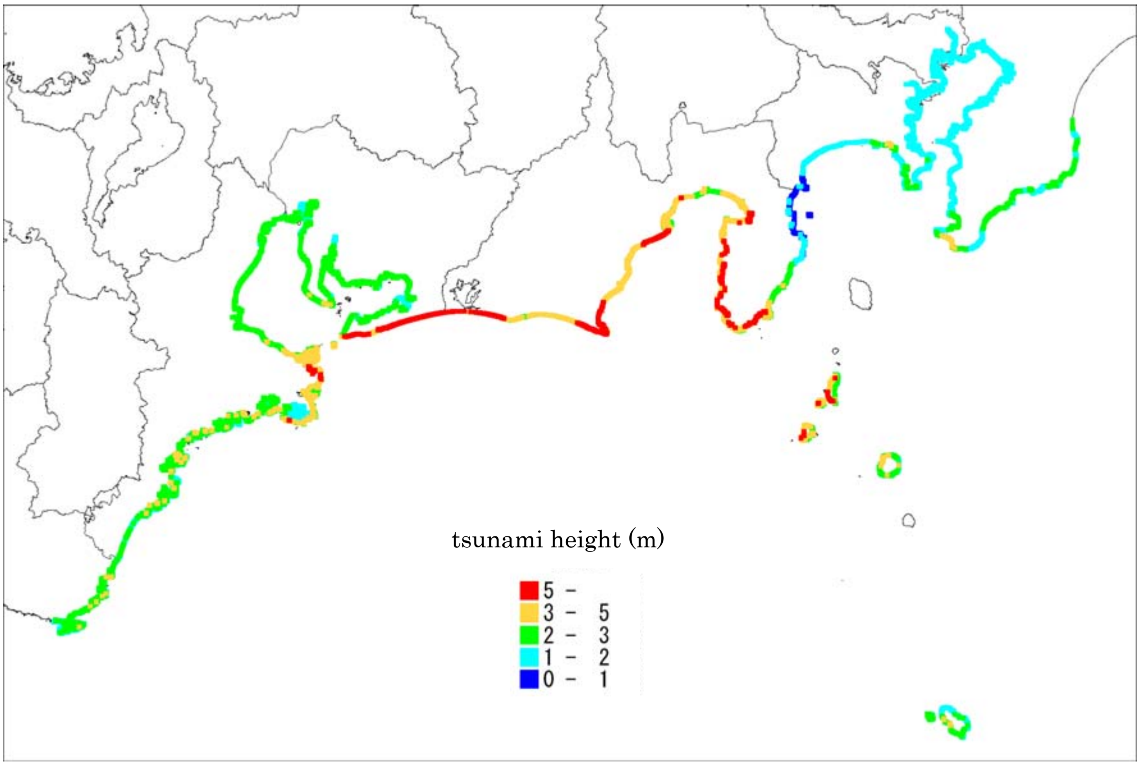

Fig. 12 Tsunami height due to the Tokai earthquake.

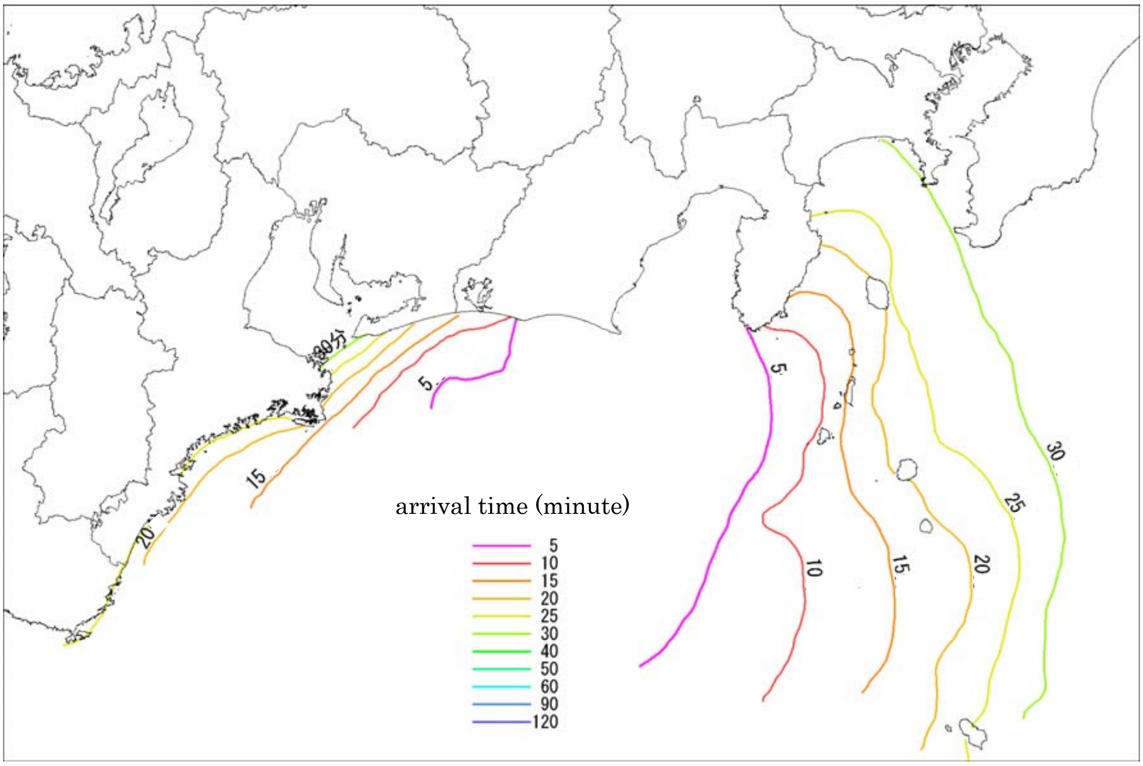

Fig. 13 Tsunami travel time due to the Tokai earthquake.

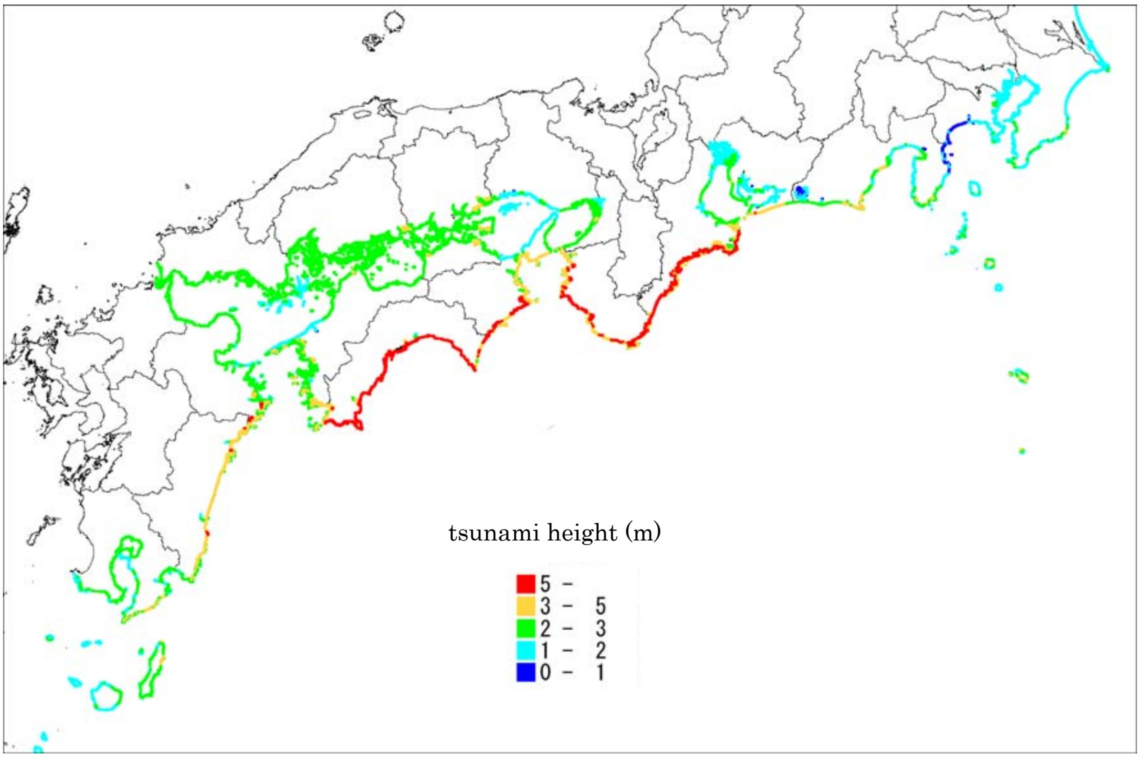

Fig. 14 Tsunami height due to the Tonankai-Nankai earthquake.

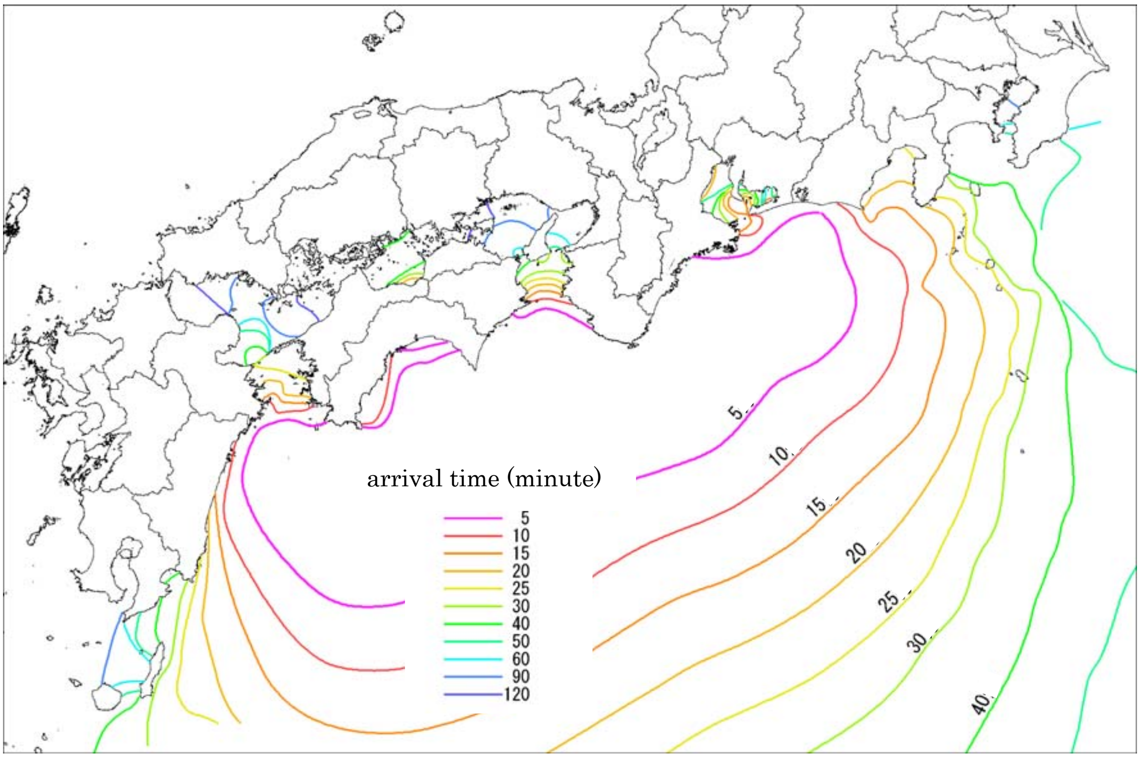

Fig. 15 Tsunami travel time due to the Tonankai-Nankai earthquake.

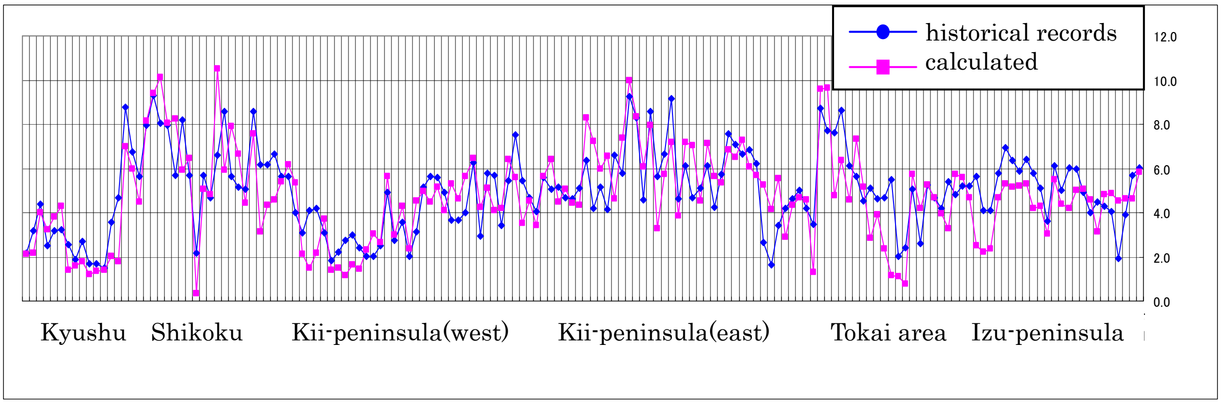

Fig. 16 Comparison of calculated tsunami heights with the observed.

As shown in Fig. 9 or Fig. 10 of the strong ground motion results, the areas near the coast suffer both strong ground motion of JMA intensity 6 or more and tsunami of 5m or higher. It is noted that large tsunami arrives in wide area damaged by strong shaking soon after the earthquake occurrence.

APPLICATION OF PREDICTIONS

Designation of areas to strengthen and to promote disaster management

According to the historical records and recent experiences on the damages due to earthquakes, JMA intensity scale of 6 or more and tsunami height of 3m or more result in severe damages to houses and buildings, which in turn results in casualties. Based on the predictions of strong ground motion and tsunami height, the national government designated the areas which will potentially suffer such hazards, as areas to strengthen and to promote earthquake disaster management. The population within the designated areas amount about 41 millions, which corresponds to 32 percent of total national population.

Estimation of damage

Damage estimation was carried out from the prediction results of strong ground motion and tsunami height. Statistical data of damages such as destruction rate of buildings and rate of casualties were adopted from the 1995 Hyogoken-Nanbu earthquake and so on. The result of estimation indicates that the Tokai earthquake or the Tonankai-Nankai earthquake ends up to the worst scenario of 260,000 or 360,000 buildings collapsed and 9,200 or 18,000 people killed, respectively. Fig. 17 and Fig. 18 respectively show the estimated distributions of totally collapsed houses per 1km by 1km mesh.

On the basis of the concrete and qualitative damage estimation, studies were carried out on earthquake disaster management, including preventive measures to prepare for earthquakes and emergency countermeasures right after the earthquake occurrence.

COUNTERMEASURES

The management for the Tokai earthquake and the Tonankai-Nankai earthquake, such as preparedness, management plan on a warning statement (for the Tokai earthquake only), and emergency response plans right after the earthquake occurrence are summarized in the general principle. The main subjects are described in the followings.

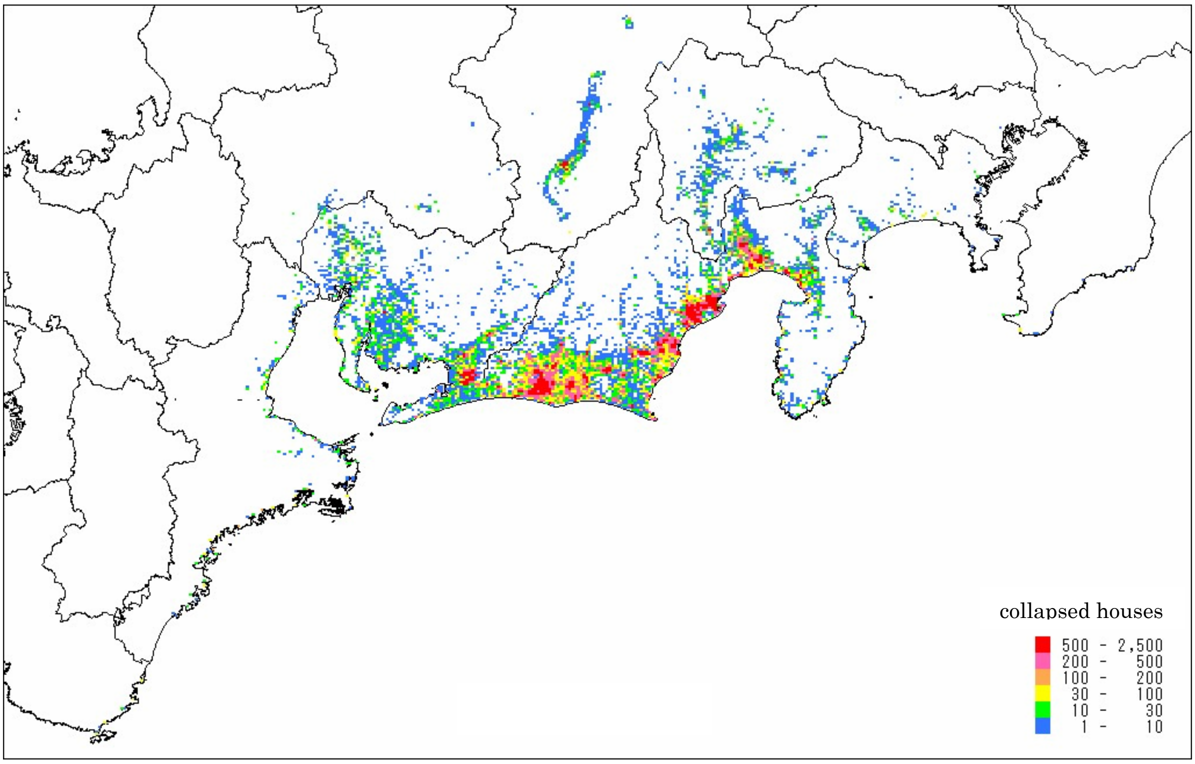

Fig. 17 Distribution of totally collapsed houses due to the Tokai earthquake.

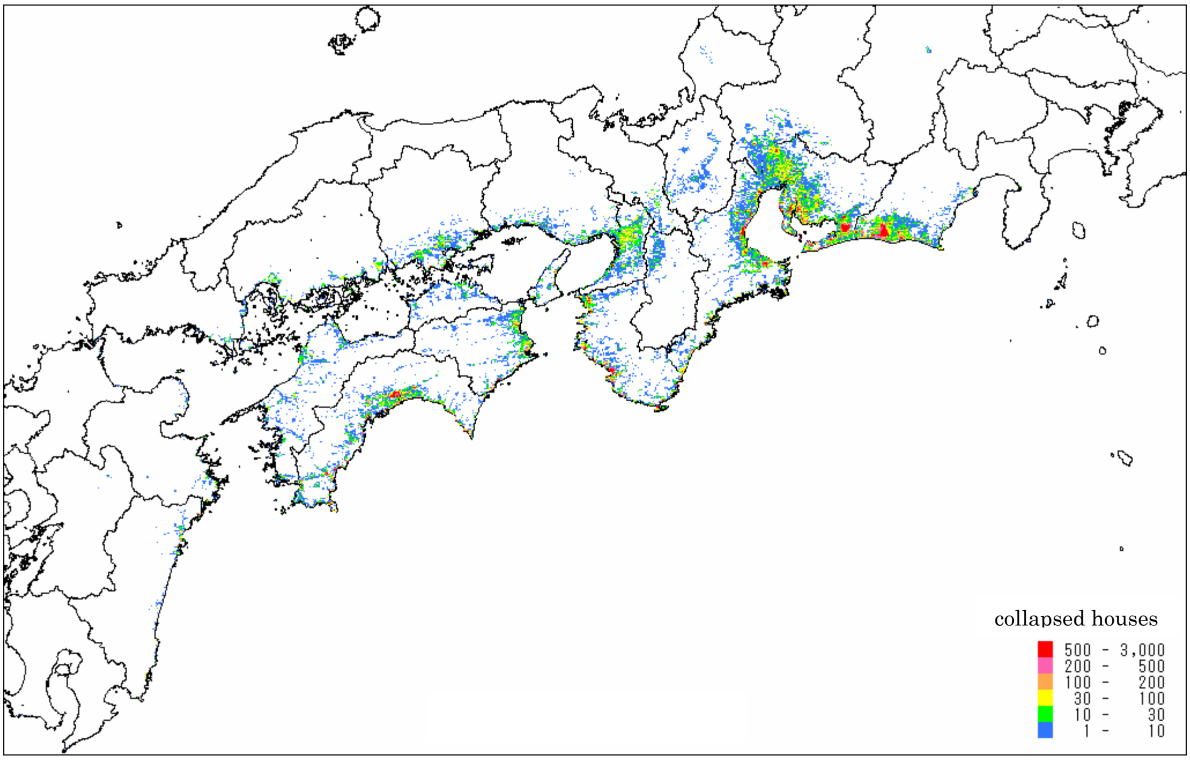

Fig. 18 Distribution of totally collapsed houses due to the Tokai earthquake.

Urgent advancement of earthquake resistance of buildings

It was observed in the 1995 Hyogoken-Nanbu earthquake that the houses and buildings which were built before the 1981 revision of building codes were relatively easily destroyed to cause casualties. This is the very reason for the large number of deaths in the damage estimation. Thus, urgent execution of diagnosis and enforcement of earthquake resistance of private residences and public buildings is included in the countermeasures as a major subject.

Strengthening local disaster prevention capability for earthquake hazard

It is confirmed through the damage estimation that the affected area is extremely wide. Thus, it is not easy for the public rescue corps like the Self-Defence Forces or the police to act very rapidly and with full treatment. Hence, the key issue is the adequate rescue operation of the local residents and enterprises by themselves. For this, thorough-going education and enlightenment is necessary of correct knowledge on earthquake, earthquake resistance of buildings, fixation of furniture, preparation like stockpile of commodities, an adequate action to take right after the earthquake occurrence.

Optimum management on issuance of a warning statement

The Tokai earthquake is so far the only event that is expected to be predicted several days before the occurrence. When predicted, the prime minister issues a warning statement of earthquake occurrence. The former scheme prescribes that all the railways, theaters, and department stores which locate in the area to strengthen disaster management must evenly suspend business, if the warning is issued. By making the most of the present precise prediction of strong ground motion and tsunami, the new scheme allows continuation of business in areas of relatively low hazards.

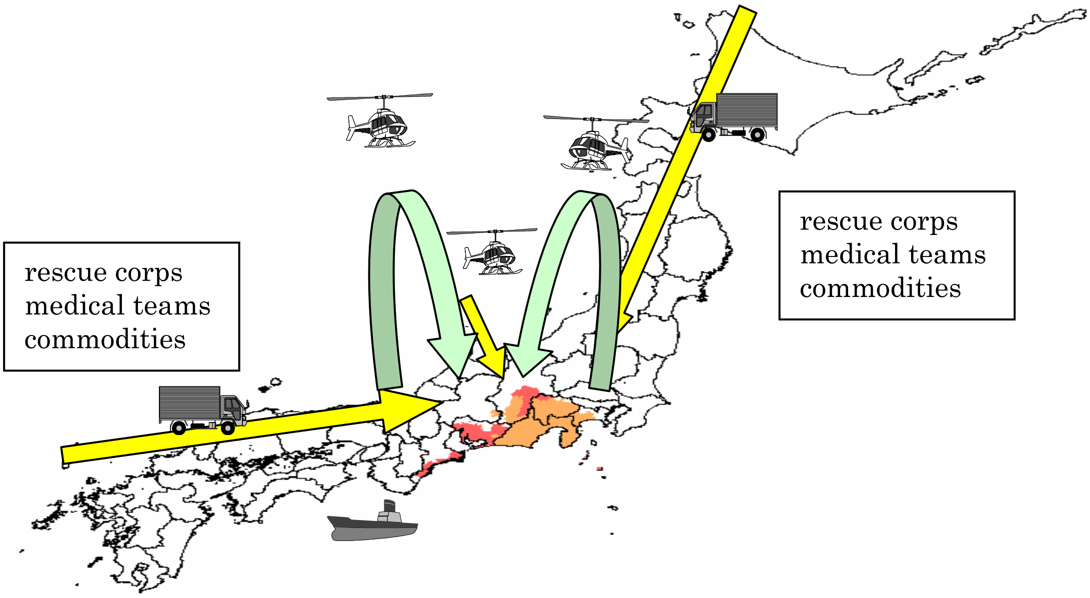

Fig. 19 Early response planned on the basis of the damage estimation.

Establishment of effective wide-area emergency response operations

Extremely wide area is affected by strong ground motion and tsunami from the Tokai earthquake or the Tonankai-Nankai earthquake. The manual for emergency response operations is established for the effective operation of public rescue action after the earthquake occurrence. Since the affected area is very wide and it will take time to get information on local damages, it is concerned that the initial response may be delayed. To avoid this, the manual prescribes that the detachment of rescue corps and conveyance of materials should be commenced at the early stage of gaining no information to the places which are estimated by prediction that public supports are supposed to be needed because of severe damages. FIg. 19 shows the image of early response.

Promotion of tsunami countermeasures

As described in the previous section, a number of areas suffer attacks of tsunami of 5m or higher only several minutes after being damaged by strong ground motion. Also, the large tsunami waves, especially from the Tonankai-Nankai earthquake, propagate to wide area and severe damages are estimated. Thus, the tsunami countermeasure is one of major subjects to be promoted. The tsunami countermeasure includes the promotion of evacuation plans such as reserve of evacuation sites and routes, transmission of tsunami information to residents, prevalence of hazard map.

CONCLUSIONS

The huge subduction zone earthquakes, namely the Tokai earthquake, the Tonankai earthquake and the Nankai earthquake, which we introduced here, are the largest earthquakes in magnitude. Many of related agencies and services are now reviewing various plans concerning earthquake disaster management so as to prepare for the large earthquakes and to properly manage right after the earthquake occurrence. The national government, local governments, private enterprises, and local citizens are all working in cooperation to establish earthquake countermeasures.

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