13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1904

A STUDY ON HAZARD MAPS FOR INLAND AND SUBDUCTION EARTHQUAKES IN JAPAN

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SUMMARY

A hazard map for a scenario earthquake represents a spatial strong-motion distribution that will be caused by a specified future earthquake. In order to make hazard maps for scenario earthquakes in Japan, a methodology to evaluate a spatial strong-motion distribution is established. The long-term evaluation results of earthquakes in Japan presented by the Headquarters for Earthquake Research Promotion are reflected on this study. Heterogeneous fault models of possible earthquakes are established by considering asperities in which slips and stress drops are larger than those in the background on the fault plane. Three-dimensional propagation characteristics of seismic waves and the amplification in surface layers are estimated based on detailed information and data collected in the mapping area. The strong-motion time histories, peak values and seismic intensities are evaluated by using the theoretical, semi-empirical and empirical methods at all the points which are arranged regularly all over the mapping area with almost 1 km spacing. The developed procedure and techniques are applied to several inland and subduction earthquakes in Japan.

INTRODUCTION

Recently, long-term evaluations of inland earthquakes along the major active faults in Japan and those of large earthquakes along the subduction zones around Japan, have been presented by the Headquarters for Earthquake Research Promotion. They are based on the newest information and data of active faults and of historical earthquakes, which have been obtained from a lot of research works and surveys. A long-term evaluation result contains the location, the size, the shape, and some related information of a fault, magnitude and probability of a possible earthquake. They are fundamental to setting fault parameters useful to evaluate ground motions and reflected to the hazard maps for scenario earthquakes.

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[5] Mitsubishi Space Software Co., Ltd.

This paper introduces the methodology to make hazard maps for scenario earthquakes. Applying the proposed methodology to some possible earthquakes in and around Japan, and based on the long-term evaluation results of them, the hazard maps for the scenario earthquakes are evaluated and are illustrated.

METHODOLOGY TO MAKE HAZARD MAPS

A hazard map for a scenario earthquake represents a spatial strong-motion distribution in an area that will be caused by a specified future earthquake. In order to make a lot of hazard maps for scenario earthquakes in Japan, a methodology is proposed (Fujiwara et al. [1], Ishii et al. [2], Fujiwara et al. [3]). The following is the outline of the proposed methodology described.

Modeling of Faults of Scenario Earthquakes

The characterized fault models of the scenario earthquakes are established by considering the asperities in which slips and stress drops are larger than those in the background area on the fault plane. Figure 1 shows the procedure to determine a characterized fault model of a scenario earthquake.

Step 1: Estimation of Seismic Source Fault

A lot of information and data are collected in and around the fault area of the scenario earthquake. Most of them are identified as the results of the long-term evaluations. There might be other additional information or data that should be collected in order to evaluate strong motions. After discussing them all carefully, the seismogenic active fault, the seismogenic zone and the locked zone are identified.

Step 2: Determination of Fault Parameters

Based on the seismic source fault mentioned above, the fault parameters are determined with the help of some empirical relations between the parameters.

Step 3: Determination of Heterogeneous Fault Parameters

Based on the above mentioned fault parameters, next, the heterogeneous fault parameters in the asperities and the background of the fault plane are determined with the help of some empirical relations between the parameters.

Step 4: Determination of Other Parameters

The parameters related to the rupture characteristics on the fault plane are determined. If there are not sufficient information or data to judge the most probable parameter, some different cases of scenarios with different parameters might be adopted.

Modeling of Underground Structures

Three-dimensional propagation characteristics of seismic waves are estimated based on the detailed information and data collected in the mapping area. The seismic wave propagation model consists of three contents. The first is the deep underground structure from the fault plane up to the seismic bedrock where the S wave velocity is about 3km/s. The second is the sedimental structure from the seismic bedrock up to the engineering bedrock where the S wave velocity is about 400 to 700m/s. The third is the amplification in the surface layer from the engineering bedrock up to the ground surface.

Strong Motion Evaluation and Hazard Maps for Scenario Earthquakes

Figure 2 shows the procedure to evaluate hazard maps for scenario earthquakes. The strong-motion time histories at the engineering bedrocks, peak values of ground motions and seismic intensities are evaluated by using the theoretical, semi-empirical and empirical methods at all the points which are arranged regularly all over the mapping area with about 1 km spacing. The empirical method, as shown in the left of Figure 2, estimates only peak values and seismic intensities by using the empirical relations between the parameters (Si and Midorikawa [4], Matsuoka and Midorikawa [5], Midorikawa et al. [6]). The hybrid method, as shown in the right of Figure 2, using the theoretical method in longer period and the semi-empirical method in shorter period, enables to evaluate broadband strong-motion time histories and to discuss the detailed characteristics of strong-motion distribution close-by and around the fault.

APPLICATIONS TO HAZARD MAPS FOR SCENARIO EARTHQUAKES

The developed procedure and techniques are applied to several possible earthquakes whose probabilities of occurrence are estimated to be higher as the results of the long-term evaluations (Earthquake Research Committee [7,8,9,10]). The followings are some examples shown with the fault models established and the hazard maps evaluated.

Inland Earthquakes: Hypothetical Itoigawa-Shizuoka Tectonic Line Earthquakes

Itoigawa-Shizuoka Tectonic Line Fault Zone is located almost in the middle of Honshu, the main island of Japan. It is one of the largest and the most active faults in Japan. According to the result of the long-term evaluation (E.R.C. [7]), the possibility of occurrence of an earthquake with the magnitude about 8 is estimated to be high along the north and middle parts of this fault zone. The developed procedure and techniques are applied to these parts.

Fault Models of Scenario Earthquakes

The fault models of the scenario earthquakes are established and illustrated in the left of Figure 3. The sum of areas of the fault planes is 1905.4 km^2. It is composed of two reverse segments in the north part and two strike slip segments in the middle part of the fault zone. The total seismic moment is 1.5E+20 N*m. The short period level is estimated to be 2.82E+19 N*m/ s^2 as shown in the top left of Figure 4, that corresponds the average value in the historical earthquakes (Dan et al. [11]). Each segment has one asperity where the effective stress is 13.1 MPa. As shown in the bottom left of Figure 3, three cases of scenarios with different asperity arrangements are taken into account since there is not enough information to determine the possible position of asperities in the north part of the fault zone.

Underground Structures

The mapping area is also shown in the top left of Figure 3. It is determined so as to cover the area in which, by using the empirical method, the seismic intensity is estimated up to 6 or larger. The deep underground structure, the sedimental structure and the amplification in the surface layers are modeled.

Strong-Motion Evaluation and Hazard Maps

The strong-motion time histories at the engineering bedrocks are evaluated by using the hybrid method. In the top right of Figure 4, the evaluated peak velocities are normalized into the equivalent values in which S wave velocity is 600 m/s, and compared with the attenuation relations (Si and Midorikawa [4]). The evaluated velocities correspond very well to the attenuation relations.

Shown in the bottom left of Figure 4 are the examples of the evaluated strong motions at the six points that are marked in the top left of Figure 3. The examples of the evaluated pseudo velocity response spectra are also shown in the bottom right of Figure 4. At HOT and MTS, just in front of the largest asperity in Case 1, the durations of strong motions are very short and the amplitudes become huge, more than 80 cm/s, because of the near fault rupture directivity effect. At KOF, large long-period waves which have been generated in the deep sediments can be seen in the later part of the time history and their spectral amplitudes in longer period range become larger than those in shorter period range.

The peak velocities at the engineering bedrocks and the seismic intensities in J.M.A. scale at the ground surface are calculated from the evaluated time histories at all the points which are arranged regularly all over the mapping area with about 1 km spacing. Shown in the right of Figure 3 are the spatial distributions of the peak velocities and the seismic intensities. In the northern area, the spatial distributions of huge ground-motion areas are different between the cases because of the different asperity locations. The seismic intensities reach six or more in the area just in front of the rupture through shallow asperities. In the southern area, the spatial distributions are almost same.

Subduction Earthquakes: Hypothetical Miyagi-ken-oki Earthquakes

Off the Pacific coast of Miyagi Prefecture that is located in Tohoku, the northeast of the main island of Japan, large earthquakes occurred many times in history. They are named Miyagi-ken-oki earthquakes, literally "Earthquakes off the coast of Miyagi Prefecture" in Japanese. They are the most active inter-plate large earthquakes along the Pacific coast of northeast Japan. The last event occurred in 1978 and caused large disaster in and around Sendai City. The event once before occurred in 1936. According to the result of the long-term evaluation (E.R.C. [8]), the possibility of occurrence of an earthquake with the magnitude about 7.5 is estimated to be very high in the area off the coast of Miyagi Prefecture. They also say the location of asperities in 1978 and that in 1936 are different a little. The developed procedure and techniques are applied to both of these areas.

Fault Models of Scenario Earthquakes

Two fault models of the scenario earthquakes, Models A1 and A2, are established and illustrated in the top of Figure 5. Both of them are reverse faults along the subduction zone off the coast of Miyagi Prefecture.

Model A1 is the type of the event in 1978. The sum of area of the fault plane is 2266 km^2. The seismic moment is 3.10E+20 N*m and the short period level is estimated to be 8.38E+19 N*m/ s^2 as shown in the top left of Figure 6. The short period level of the scenario earthquake is determined almost 2.3 times as much as the average value in the historical earthquakes (Dan et al. [11]), that well corresponds the values in the earthquakes along the plate boundary off the Pacific coast of Japan (Satoh et al. [12], Kato and Takemura [13], Satoh et al. [14], Satoh and Tatsumi [15]). The locations of two asperities are determined based on the ones in 1978. The effective stress is 29.0 MPa at the west one and 72.6 MPa at the east one just beside the rupture origin.

Model A2 is the type of the event in 1936. The sum of area of the fault plane is 1449 km^2. The seismic moment is 1.58E+20 N*m and the short period level is estimated to be 6.70E+19 N*m/ s^2. The location of the asperity is determined based on the one in 1936. The effective stress is 54.1 MPa at the asperity.

Underground Structures

The deep underground structure, the sedimental structure and the amplification in the surface layers are modeled. The Pacific Plate is also taken into account in the model.

Strong-Motion Evaluation and Hazard Maps

The strong-motion time histories at the engineering bedrocks are evaluated by using the semi-empirical method. In the bottom left of Figure 6, the evaluated peak velocities of Model A1 are normalized into the equivalent values in which S wave velocity is 600 m/s, and compared with the attenuation relations (Si and Midorikawa [4]). Since the short period level of the scenario earthquake is more than twice as much as the average, the evaluated velocities are also distributing around the average plus standard deviation level of the attenuation relations.

Shown by red lines in the right of Figure 6 are the examples of the evaluated strong motions at the three stations around Sendai that are marked in the top left of Figure 5. In the figure, the records during 1978 Miyagi-ken-oki earthquake are also shown by black lines and compared with the evaluated ones. It is confirmed that the evaluated motions explain the records very well.

The peak velocities at the engineering bedrocks and the seismic intensities at the ground surface are calculated from the evaluated time histories. The middle of Figure 5 shows the spatial distributions of the peak velocities and the bottom of Figure 5 shows the ones of the seismic intensities. Generally, the strong motions are larger in Model A1. It is confirmed that the evaluated seismic intensities also explain very well the ones caused by the historical earthquakes in 1978 and in 1936, respectively.

Examples for the Other Inland Earthquakes

The developed procedure and techniques are also applied to several other inland earthquakes along the major active faults in Japan. The following is a couple of examples introduced.

Hypothetical Futagawa-Hinagu Earthquakes

Futagawa-Hinagu Fault Zone is located in the west of Kyushu, the western island of Japan. According to the result of the long-term evaluation (E.R.C. [9]), the possibility of occurrence of an earthquake with magnitude about 8 is estimated to be high along the middle and southwestern parts of this fault zone.

Figure 7 shows the fault models of Hypothetical Futagawa-Hinagu Earthquakes and the hazard maps evaluated by the hybrid method. Only the middle part ruptures from north to south in Case 1 and backward in Case 2. In Cases 1 and 2, the sum of area is 667.2 km^2, the seismic moment is 2.48E+19 N*m, the short period level is 1.55E+19 N*m/ s^2 and the effective stress at each asperity is 13.6 MPa. In Case 3, both of the middle and southwestern parts rupture separately, the sum of area is 1034.2 km^2, the seismic moment is 5.95E+19 N*m, the short period level is 2.07E+19 N*m/ s^2 and the effective stress at each asperity is 12.6 MPa.

Hypothetical Miura Peninsula Earthquakes

Miura Peninsula Faults are located in the south of Tokyo metropolitan area, Japan. According to the result of the long-term evaluation (E.R.C. [10]), the possibility of occurrence of an earthquake with the magnitude more than 6.5 is estimated to be high along Takeyama Fault Zone, and also the one with the magnitude more than 6.7 along Kinugasa-Kitatake Fault Zone.

Figure 8 shows the fault models of Hypothetical Miura Peninsula Earthquakes and the hazard maps evaluated by the hybrid method. In Cases 1 and 2, Takeyama Fault Zone ruptures and the dip angle is assumed to be 45 degrees, the sum of area is 340.0 km^2, the seismic moment is 6.40E+18 N*m, the short period level is 9.80E+18 N*m/ s^2 and the effective stress at the asperity is 22.0 MPa. In Case 3, Takeyama Fault Zone ruptures, the dip angle is 60 degrees, the sum of area is 278.0 km^2, the seismic moment is 4.40E+18 N*m, the short period level is 8.70E+18 N*m/ s^2 and the effective stress at the asperity is 22.8 MPa. In Case 4, Kinugasa-Kitatake Fault Zone ruptures, the dip angle is 45 degrees, the sum of area is 476.0 km^2, the seismic moment is 1.26E+19 N*m, the short period level is 1.23E+19 N*m/ s^2 and the effective stress at the asperity is 20.3 MPa.

DISCUSSION

The peak velocities of the strong-motions evaluated by the hybrid method as a whole explain very well the empirical attenuation relations. In the studies on Miyagi-ken-oki earthquake, it is confirmed that the time histories of the ground motions evaluated by the semi-empirical method explain the records very well. These evaluation results mean that the developed procedure and techniques will be available for the hazard maps for the future earthquakes.

Especially for the inland earthquakes, the hybrid method is very effective to evaluate the spatial-temporal characteristics of the strong-motions. For example, in the area just in front of the rupture through shallow asperities, the amplitudes become huge, the seismic intensities reach six or more, and the durations of strong motions become very short, because of the near fault rupture directivity effect. Where an asperity is rather close, the amplitudes of strong motions will be larger relatively. The spatial distributions of huge ground-motion areas are different between the cases of the different scenarios mainly because of the asperity locations and the rupture patterns. In large and deep sediments are generated different kinds of seismic waves, for example long-period surface waves which can be seen in the later parts of time histories of the evaluated ground motions, and their spectral amplitudes in longer period range become larger than those in shorter period range. Such evaluations could not be obtained from the empirical method only. It means the reliable evaluations of time histories are very important.

In this study, the most probable parameters are estimated and adopted in order to evaluate strong motions. However the information and data concerning the natural earthquakes, active faults, underground structures and strong motion characteristics, are not sufficient yet. There still exist uncertainties in such evaluations. Since strong motions caused by large earthquakes are not so frequent events, the evaluation results should be carefully checked using the natural information and data. Of course it will be possible and necessary to improve the procedure and techniques to evaluate strong motions by using the results of researches and surveys that will be newly performed in the future.

ACKNOWLEDGMENTS

This study was performed under the direction of the Earthquake Research Committee of Japan (Chairman: Kenshiro Tsumura), the Subcommittee for Long-term Evaluations (Chairman: Kunihiko Shimazaki) and the Subcommittee for Evaluations of Strong Ground Motion (Chairman: Kojiro Irikura) (E.R.C. [16,17,18,19]).

REFERENCES

1. Fujiwara, H., S. Aoi, S. Kawai, T. Ishii, T. Okumura and Y. Hayakawa. “National seismic hazard mapping project of Japan”, IUGG2003, SS04b/10P/D-015, 2003.
2. Ishii, T., H. Fujiwara, S. Aoi, T. Sato, M. Watanabe, T. Satoh, S. Matsushima, T. Hayakawa, H. Shinohara, K. Iwamoto, K. Nozaki and S. Senna. “A study on hazard maps for scenario earthquakes in Japan”, IUGG2003, SS04b/10P/D-024, 2003.
3. Fujiwara, H., S. Aoi, S. Kawai, S. Senna, T. Ishii, T. Okumura and Y. Hayakawa. “Outline of strong-motion evaluation in seismic hazard mapping project of Japan”, 13th WCEE, 2004.
4. Si, H. and S. Midorikawa. “New attenuation relationships for peak ground acceleration and velocity considering effects of fault type and site condition”, Journal of Structural and Construction Engineering, Transaction of Architectural Institute of Japan, No.523, pp.63-70, 1999. (in Japanese)
5. Matsuoka, M. and S. Midorikawa. “The digital national land information and seismic microzoning”, Proceedings of the 22nd symposium of earthquake ground motion, pp.23-34, 1994. (in Japanese)
6. Midorikawa, S., K. Fujimoto and I. Muramatsu. “Correlation of new J.M.A. instrumental seismic intensity with former J.M.A. seismic intensity and ground motion parameters”, Journal of ISSS, Vol.1, pp.51-56, 1999. (in Japanese)
7. Earthquake Research Committee. “Survey and Evaluation of Itoigawa-Shizuoka Tectonic Line Fault Zone (September 1, 1996)”, 1996. (in Japanese)
8. Earthquake Research Committee. “Long-term evaluation of earthquakes in the sea off Miyagi Prefecture (November 27, 2000; corrected on March 14, 2001; recorrected on November 12, 2003)”, 2003, (in Japanese)
9. Earthquake Research Committee. “Evaluation of Futagawa-Hinagu Fault Zone (May 8, 2002; corrected on May 9, 2002)”, 2002. (in Japanese)
10. Earthquake Research Committee. “Evaluation of Active Faults of Miura Peninsula (October 9, 2002)”, 2002. (in Japanese)
11. Dan, K., M. Watanabe, T. Sato and T. Ishii. “Short-period source spectra inferred from variable-slip rupture models and modeling of earthquake faults for strong motion prediction by semi-empirical

method", Journal of Structural and Construction Engineering, Transaction of Architectural Institute of Japan, No.545, pp.51-62, 2001. (in Japanese)

12. Satoh, T., H. Kawase and T. Sato. "Statistical spectral characteristics for engineering bedrock waves in which local site effects of surface geology are removed", Journal of Structural and Construction Engineering, Transaction of Architectural Institute of Japan, No.462, pp.79-89, 1994. (in Japanese)
13. Kato, K. and M. Takemura. "Regional variation of source spectra in high-frequency range determined from strong motion records", Vol.2, No.51, pp.123-138, 1998
14. Satoh, T., Y. Kobayashi and K. Yashiro. "High-frequency Fourier spectra of strong motions - fmax and stress drop -", Journal of Structural and Construction Engineering, Transaction of Architectural Institute of Japan, No.527, pp.79-87, 2000. (in Japanese)
15. Satoh, T. and Y. Tatsumi. "Source, path, and site effects for crustal and subduction earthquakes inferred from strong motion records in Japan", Journal of Structural and Construction Engineering, Transaction of Architectural Institute of Japan, No.556, pp.15-24, 2002. (in Japanese)
16. Earthquake Research Committee. "Strong-motion evaluation for scenario earthquakes in Itoigawa-Shizuoka Tectonic Line Fault Zone (Northern, Central areas) as a putative earthquake generating fault (interim report) (May 25 2001)", 2001. (in Japanese)
17. Earthquake Research Committee. "Strong-motion evaluation for scenario earthquakes in the sea off Miyagi Prefecture (interim report) (October 15 2002)", 2002. (in Japanese)
18. Earthquake Research Committee. "Strong-motion evaluation for scenario earthquakes in Futagawa-Hinagu Fault Zone (interim report) (July 31, 2003)", 2003. (in Japanese)
19. Earthquake Research Committee. "Strong-motion evaluation for scenario earthquakes in Active Faults of Miura Peninsula (interim report) (October 28, 2003; corrected on December 19, 2003)", 2003. (in Japanese).

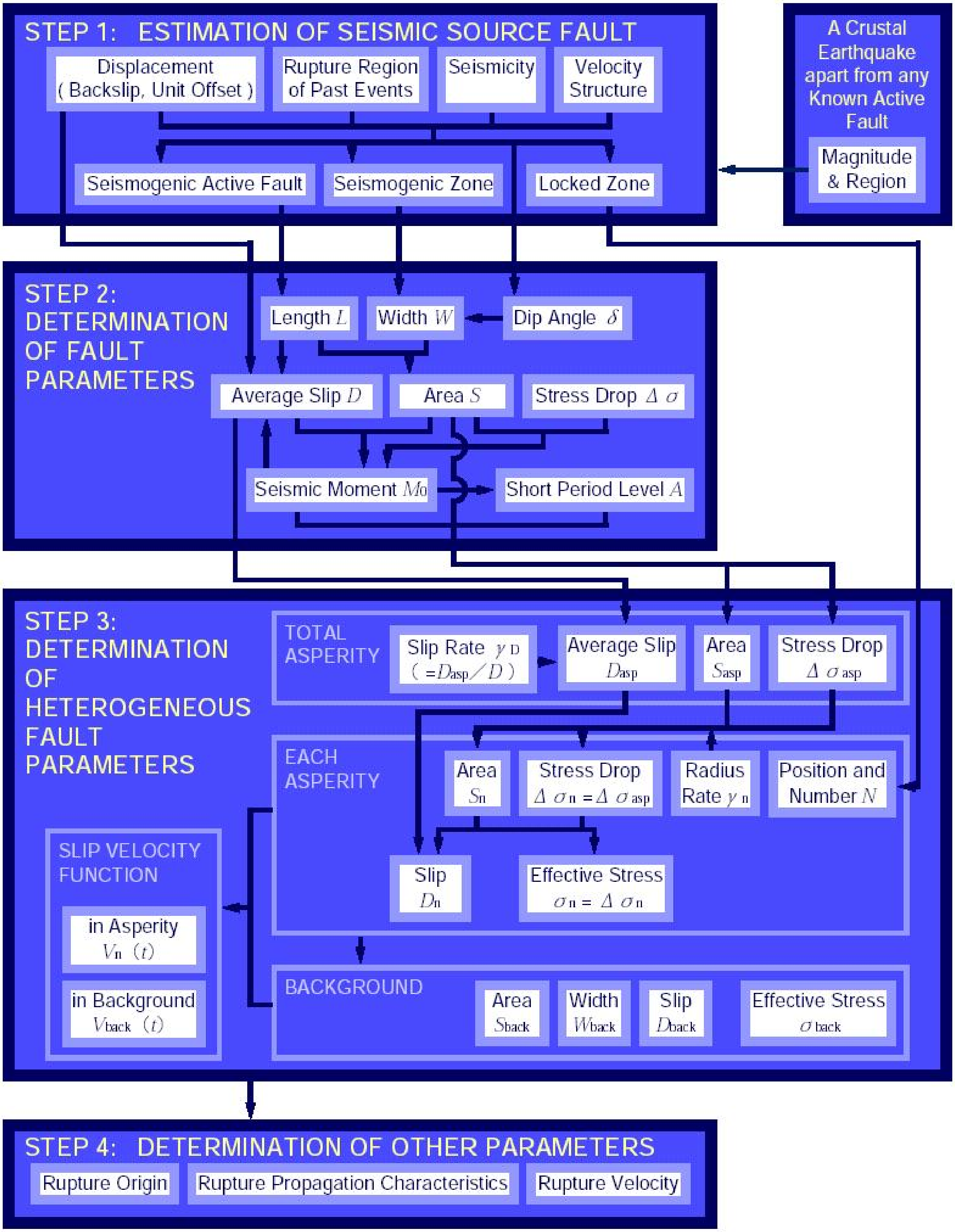


Figure 1 Procedure to Determine Characterized Fault Models of Scenario Earthquakes

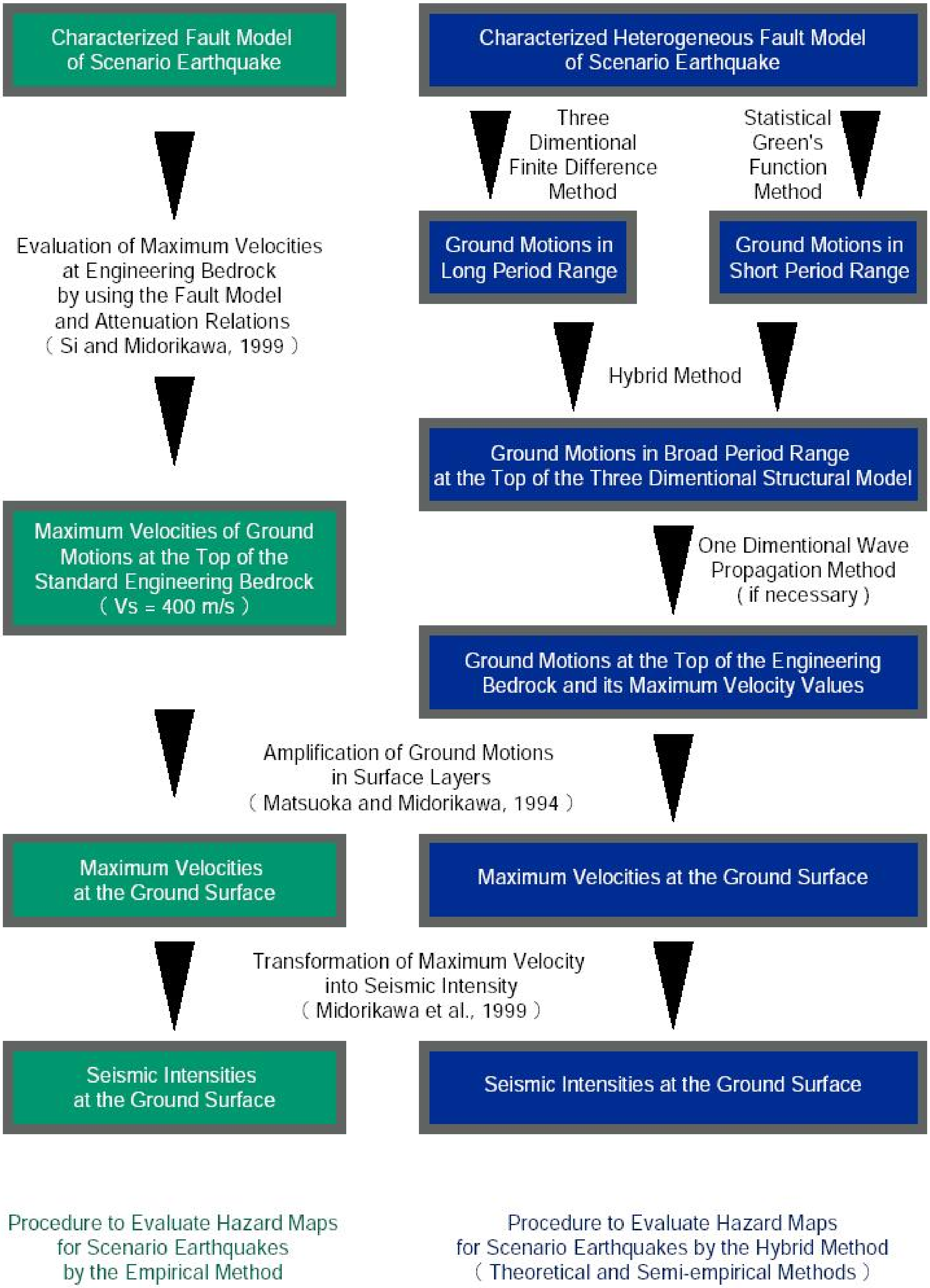


Figure 2 Procedure to Evaluate Hazard Maps for Scenario Earthquakes

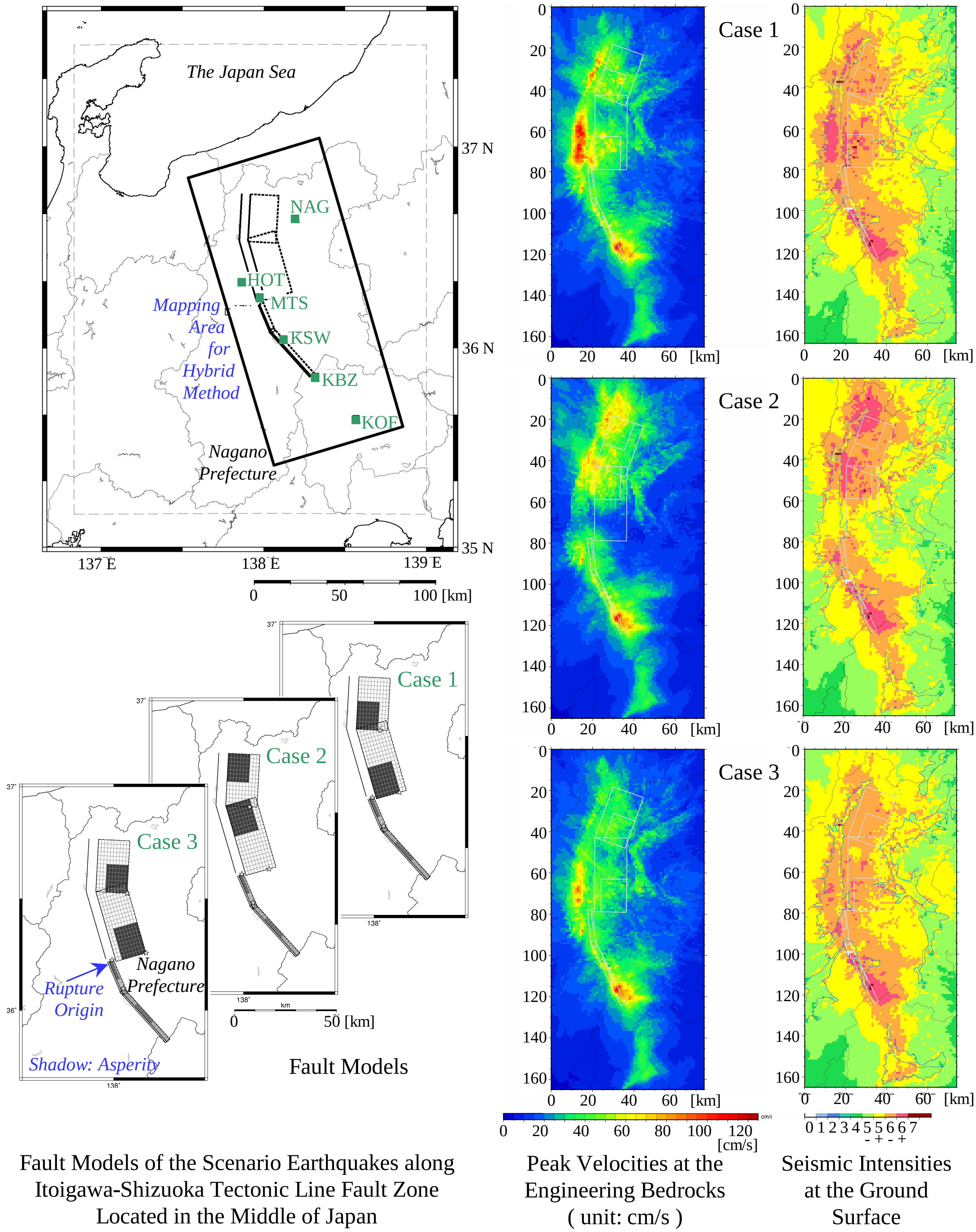
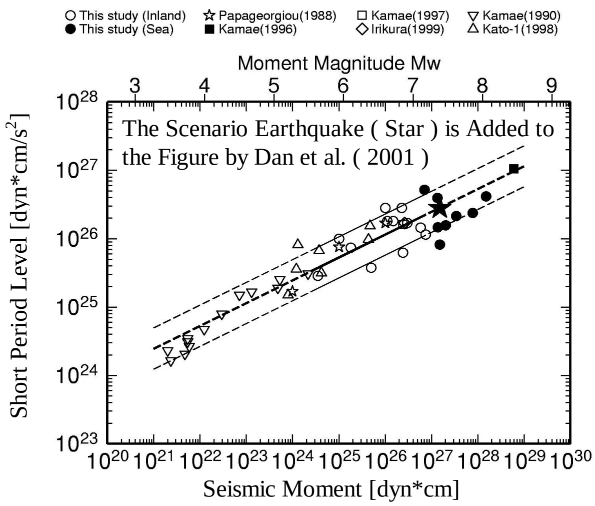
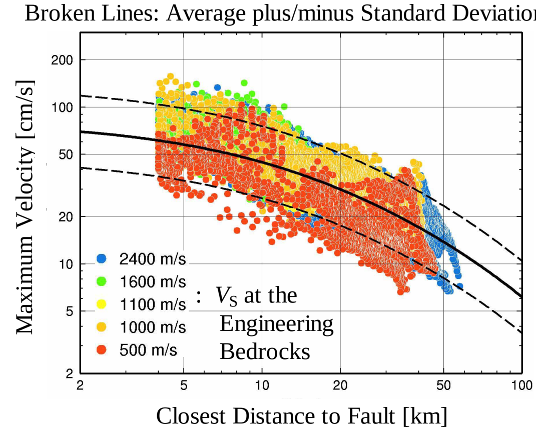


Figure 3 Fault Models of Hypothetical Itoigawa-Shizuoka Tectonic Line Earthquakes and Hazard Maps Evaluated by the Hybrid Method

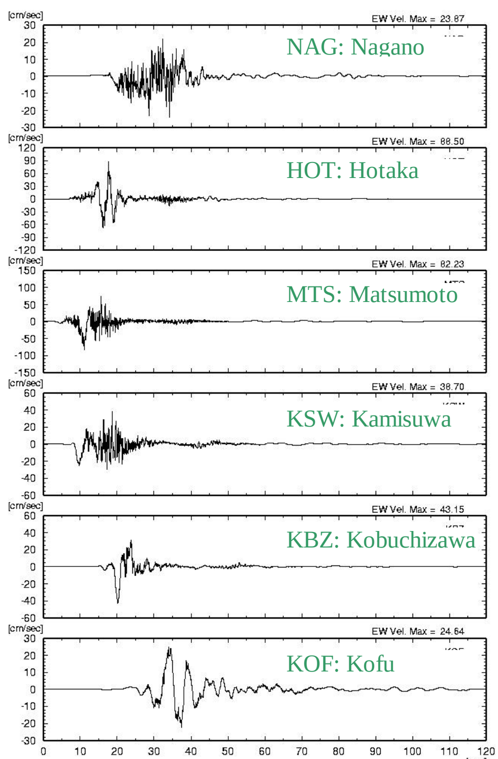


Relations between Seismic Moment
and Short Period Level

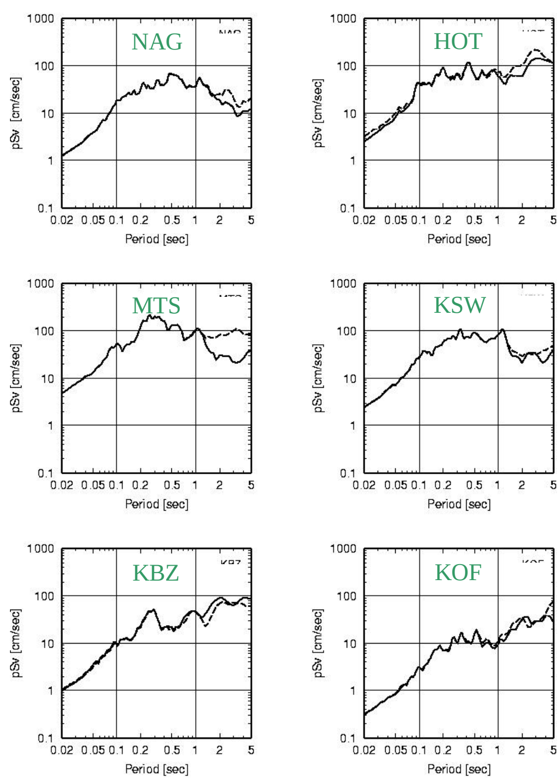
Dots: Calculated by the Hybrid Method
Lines: Attenuation Relations (Si and Midorikawa, 1999)
Solid Line: Average
Broken Lines: Average plus/minus Standard Deviation



Peak Velocities of Strong Motions
Evaluated at the Engineering Bedrocks
(Case 1, V_S is converted into 600 m/s.)



Strong Motions Evaluated
at the Engineering Bedrocks
(Case 1, EW Component, Velocity in cm/s)



Solid Lines; NS, Broken Lines; EW

Pseudo Velocity Response Spectra Evaluated
at the Engineering Bedrocks
(Case 1, Damping h = 0.05)

Figure 4 Strong Motions of Hypothetical Itoigawa-Shizuoka Tectonic Line Earthquakes Evaluated by the Hybrid Method

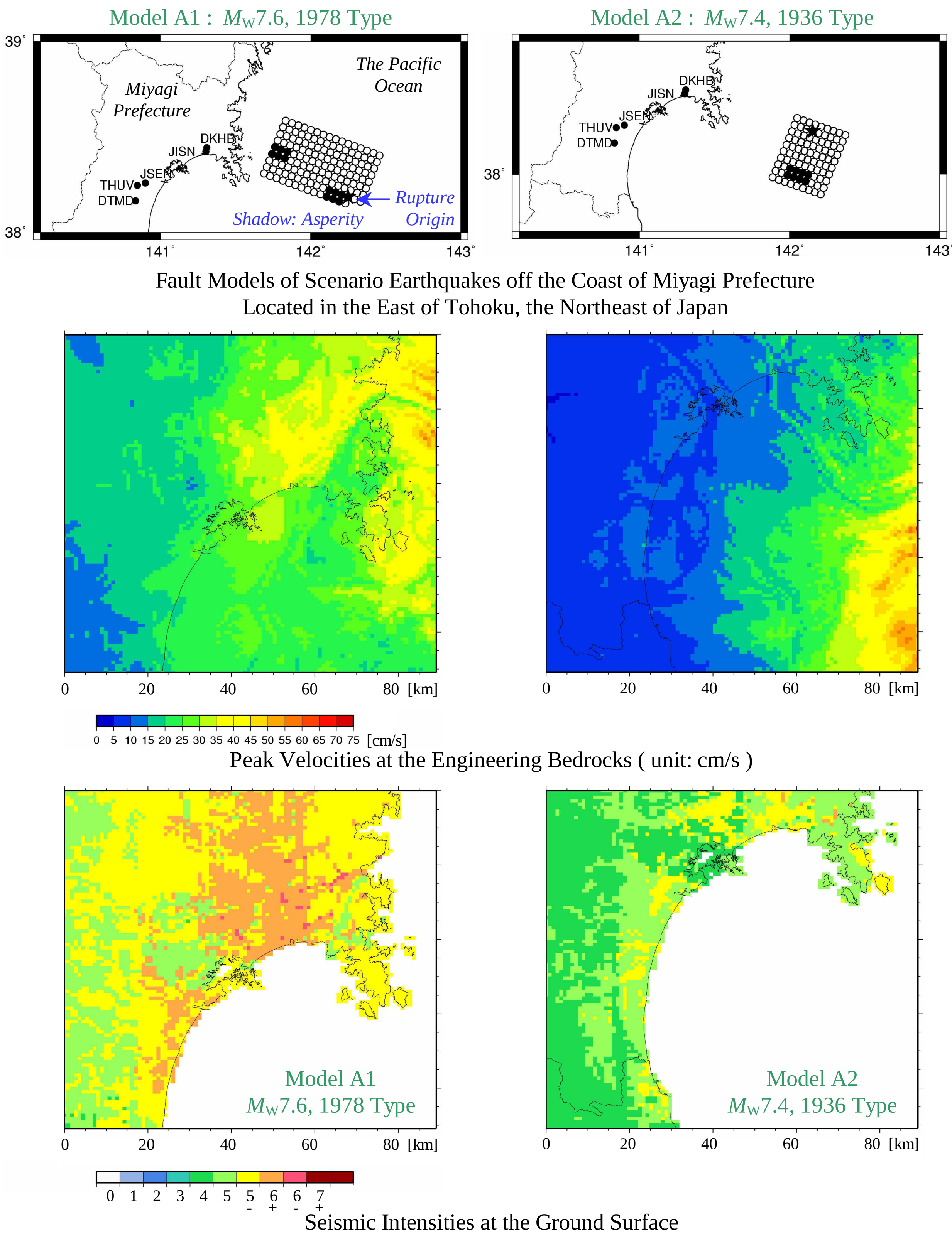
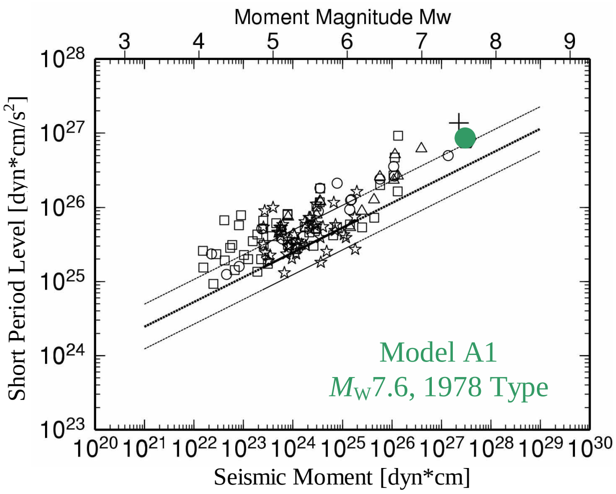


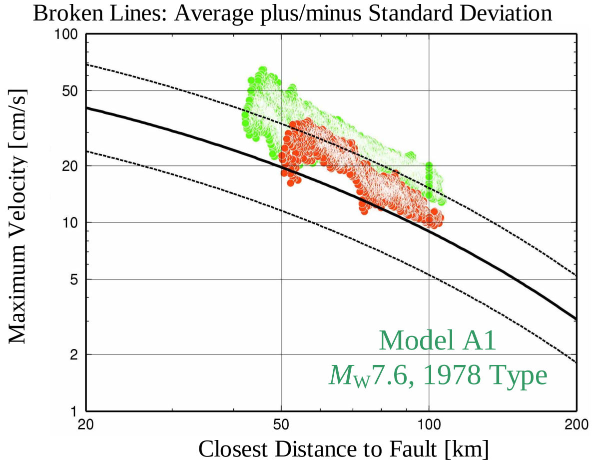
Figure 5 Fault Models of Hypothetical Miyagi-ken-oki Earthquakes and Hazard Maps Evaluated by the Semi-empirical Method

Green Circle: The Scenario Earthquake, Model A1
Lines: Empirical Relations (Dan et al., 2001)
Other Marks: Earthquakes along the Plate Boundary off the Pacific Coast of Japan
Circles: Satoh et al. (1994)
Triangles: Kato and Takemura (1998)
Squares: Satoh et al. (2000)
Stars: Satoh and Tatsumi (2002)

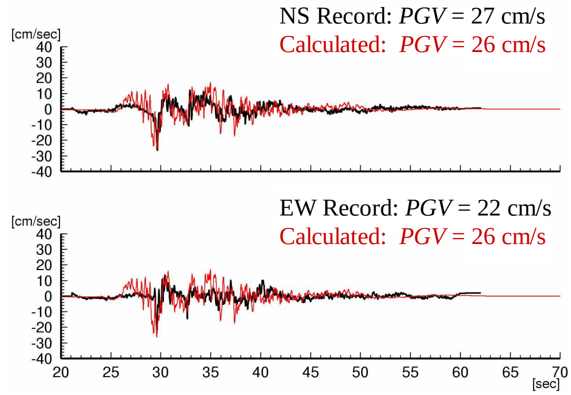


Relations between Seismic Moment and Short Period Level

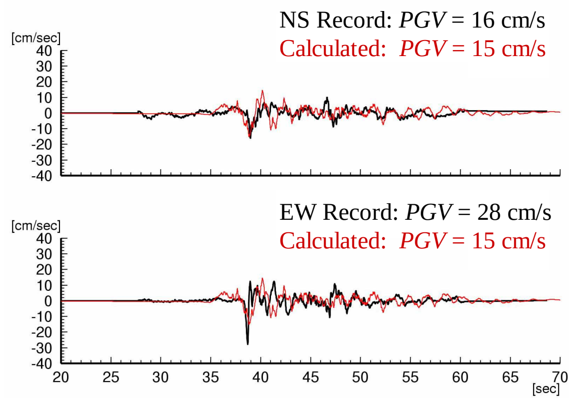
Dots: Calculated by the Semi-empirical Method
Orange: V_S is 400 m/s at the Engineering Bedrock
Green : V_S is 700 m/s at the Engineering Bedrock
Lines: Attenuation Relations (Si and Midorikawa, 1999)
Solid Line: Average
Broken Lines: Average plus/minus Standard Deviation



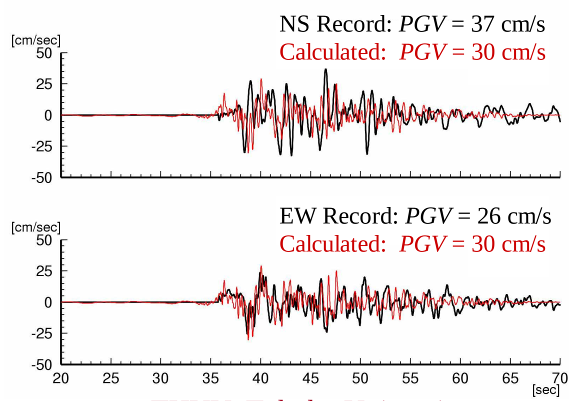
Peak Velocities of Strong Motions Evaluated at the Engineering Bedrocks (V_S is converted into 600 m/s.)



DKHB: Kaihoku Bridge



DTMD: Tarumizu Dam



THUV: Tohoku University

Comparison of Strong Motions Evaluated by Model A1 with the Velocity Records during 1978 Miyagi-ken-oki Earthquake

Figure 6 Strong Motions of Hypothetical Miyagi-ken-oki Earthquakes Evaluated by the Semi-empirical Method

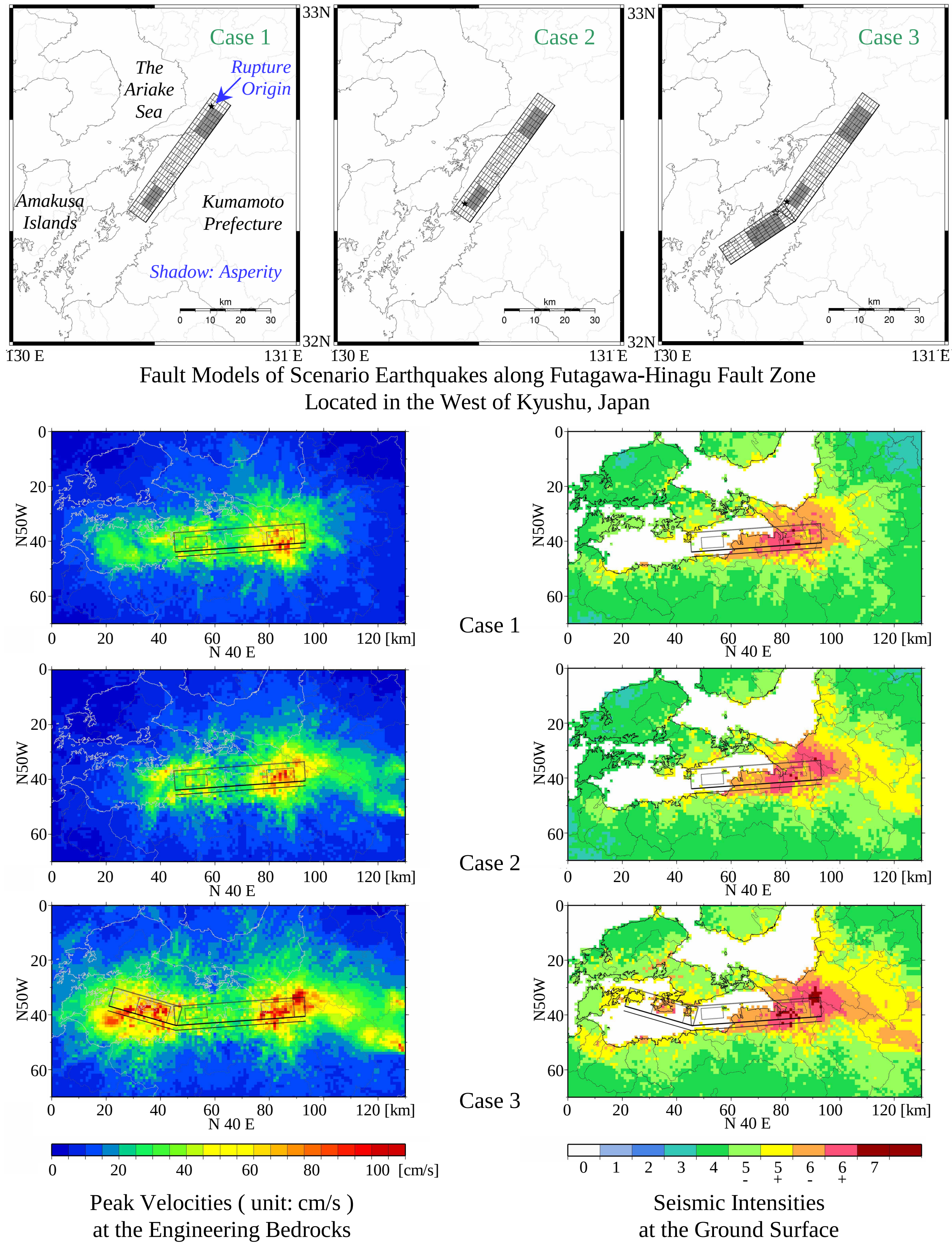
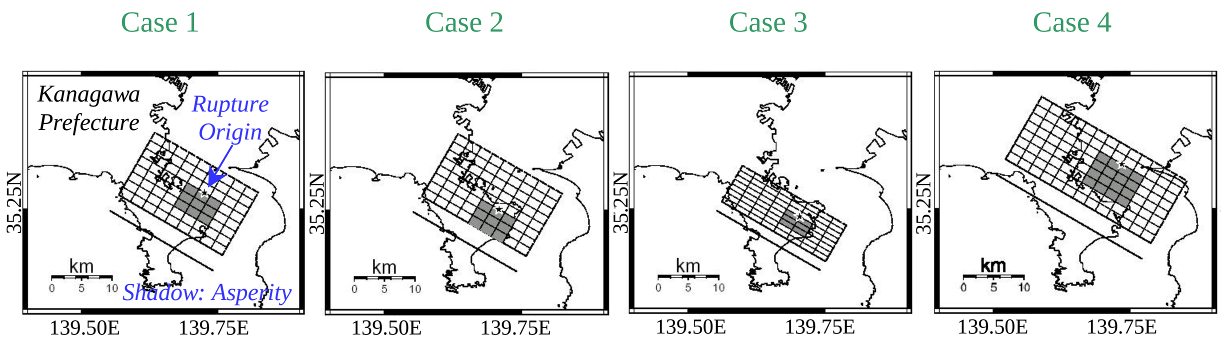
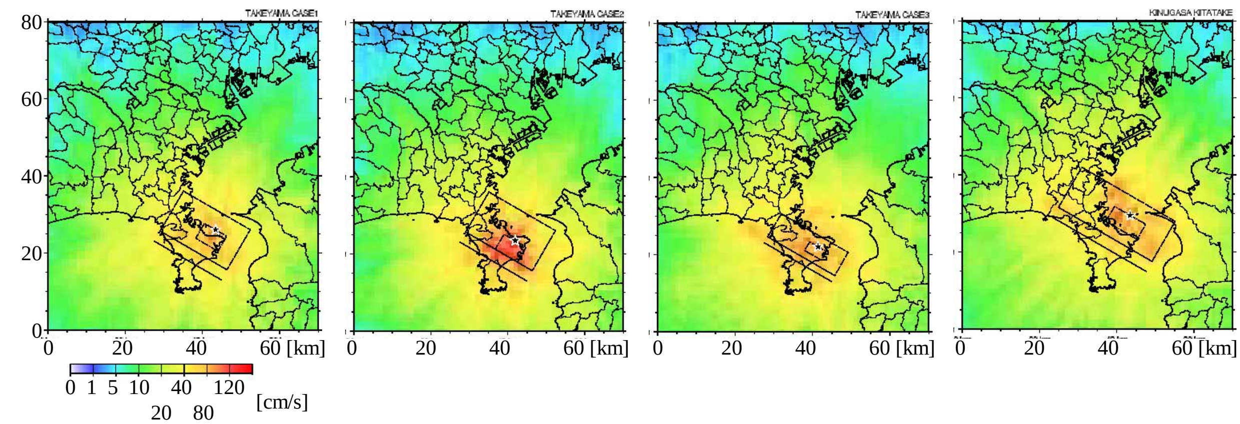


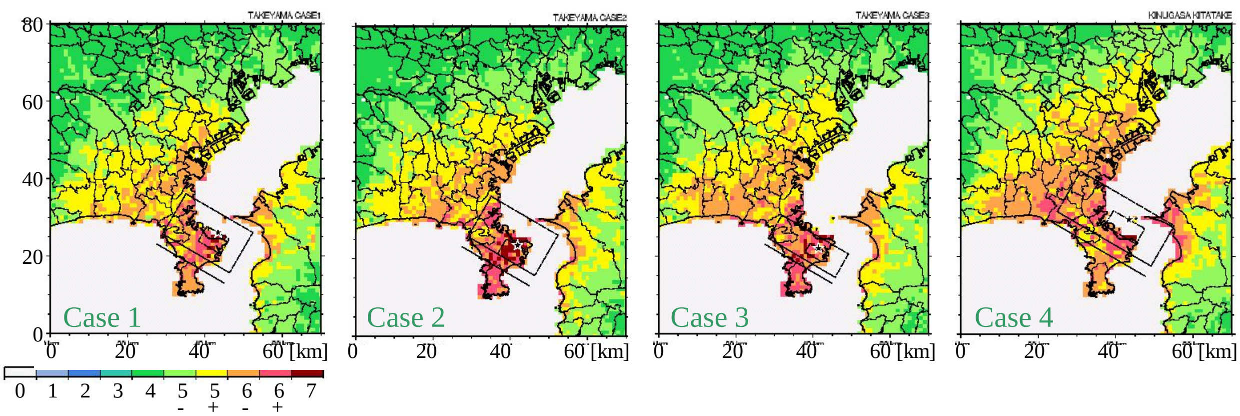
Figure 7 Fault Models of Hypothetical Futagawa-Hinagu Earthquakes and Hazard Maps Evaluated by the Hybrid Method



Fault Models of Scenario Earthquakes along Miura Peninsula Faults
Located in the South of Tokyo Metropolitan Area, Japan



Peak Velocities at the Engineering Bedrocks (unit: cm/s)



Seismic Intensities at the Ground Surface

Figure 8 Fault Models of Hypothetical Miura Peninsula Earthquakes and Hazard Maps Evaluated by the Hybrid Method