THE SURUGA BAY EARTHQUAKE OF AUGUST 11, 2009

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This reconnaissance was carried out
on the behalf of
Earthquake Disaster Investigation Committee of
Japan Society of Civil Engineers

June 2010

CONTENT

1 INTRODUCTION

The Suruga Bay earthquake occurred at 05:07, 11 August 2009 with a magnitude of 6.5 (Mj) (Mw 6.2) in the area of the anticipated Tokai earthquake according the Japan Meteorological Agency (JMA). However, the hypocenter of the earthquake is inferred to be in the subducting Philippine Sea Plate beneath Euro-Asia plate. The earthquake occurred on an unknown fault and the focal mechanism of the implied that it was due to thrust faulting, whose strike was perpendicular to that of the anticipated Tokai earthquake.

The ground motions were very high all around the Bay. The maximum ground acceleration was greater than 0.7g at Omaezaki strong motion station of the Japan Meteorological Agency (JMA). Ground amplifications were also very high, particularly in Shizuoka,

The earthquake caused the disruption of the TOMEI expressway by the failure of embankment near Makino-hara Service area, which resulted in a heavy traffic congestion for almost 5 days during the holiday period of Japan. Several roadways were also closed to traffic due to embankment as well as slope failures obstructing the roadways. Luckily there was no damage to railways.

Widespread ground liquefaction phenomenon was observed in alluvial deposits along the western shore of Suruga Bay. Ground liquefaction resulted in lateral spreading and subsidence of ground and heavy structures and uplift of light objects. There were light structural damage to port facilities due to settlement and lateral spreading. The Yaizu deep-sea water facility suffered very heavy damage. The 7.3 km long water intake pipe extending to the depth of 687m was ruptured and water intake nozzle was lost. Therefore, one of Yaizu deep-sea water pipeline had to be abandoned due to structural damage. Furthermore, the water tank was uplifted and pipe connections were damaged.

Slope failures and rock falls along steep shores of the Suruga bay were wide-spread. Although none of these slopes failures along the shores caused any damage to nearby structures, the slope failures at well-known locations were of large scale.

One of important observations was the damage to stone tombs of the cemeteries. The damage was particularly heavy in loose alluvial ground or on ridge-like ground. The damage was in the form of total collapse, dislocation due to sliding, toppling or both.

The investigation team has investigated almost all spots around the Suruga Bay. This report describes the characteristics of this earthquake and observations on various structural as well geotechnical damage and discusses lessons, which may be of great significance for the effects of the anticipated Tokai earthquake.

2 GEOGRAPHY

The earthquake is located in Suruga Bay, which is one of the deepest bay in the world and it is located in the boundaries of Shizuoka Prefecture. The earthquake was located nearby Yaizu City with a population of 143370. The capital of the Shizuoka Prefecture is Shizuoka City with a population of 760000. Shizuoka is currently the 5th largest city in Japan in terms of geographic area, and the 2nd largest city in Shizuoka prefecture in terms of population. The prefecture is mountainous and the world-famous Mount Fuji is located in the prefecture.

Tokaido Shinkansen line, Tokaido railway line, Tomei expressway and National Highway R1 pass through Shizuoka prefecture. Shizuoka also has an LRT line, the Shizuoka Railway. In other words, it connects the west and east of Japan. Any disruption of this transportation routes has a great impact on Japan. The prefecture has a new airport built nearby Yoshida town.

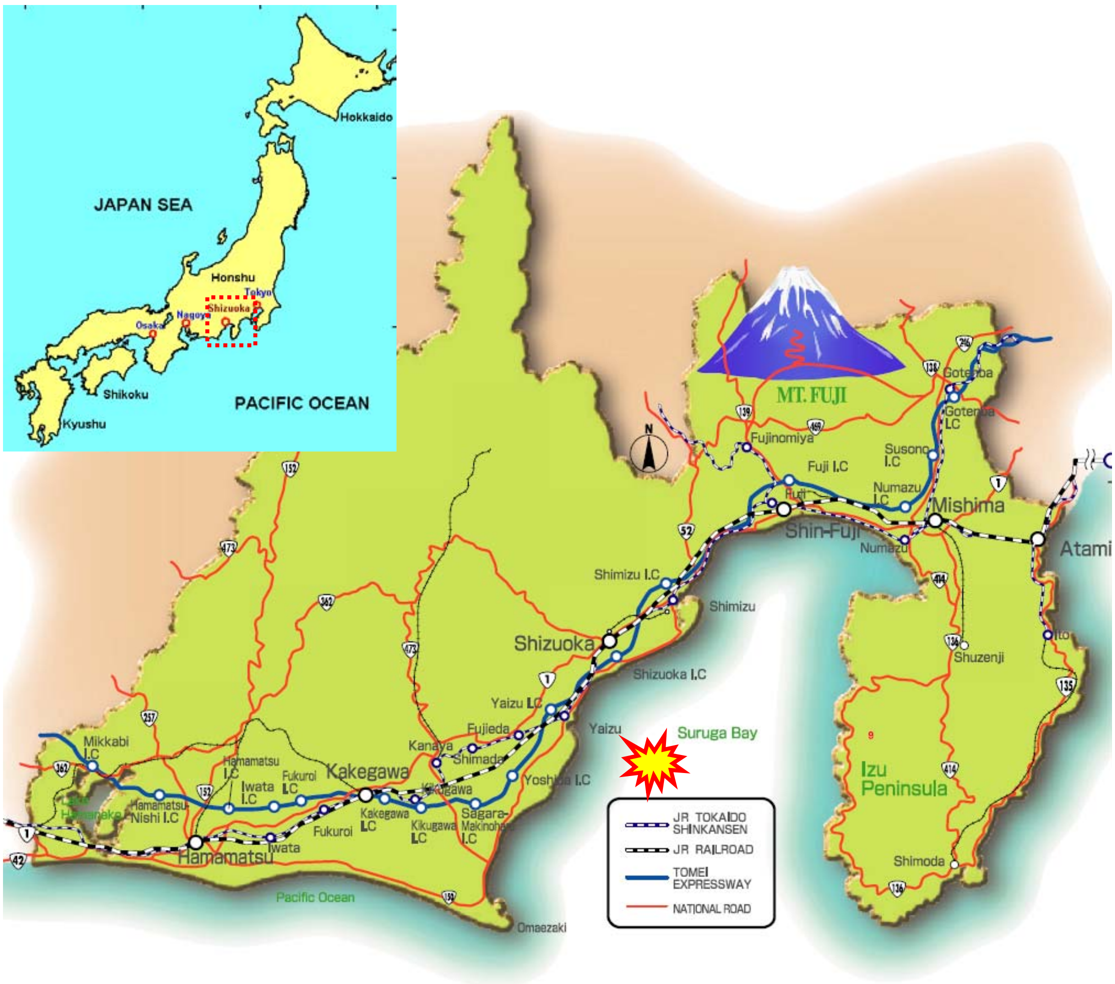


Figure 1: A geographical map of Shizuoka Prefecture

3 GEOLOGY

Figure 4 shows the geology of the Shizuoka prefecture. The eastern region and Izu peninsula of the prefecture mainly consist of volcanic sediments and volcanic rocks, while the central region composed of paleogenic and neogenic sedimentary rocks. The western region mainly consists of both paleozoic sedimentary rocks, cretaceous Shimanto belt and metamorphic rocks.

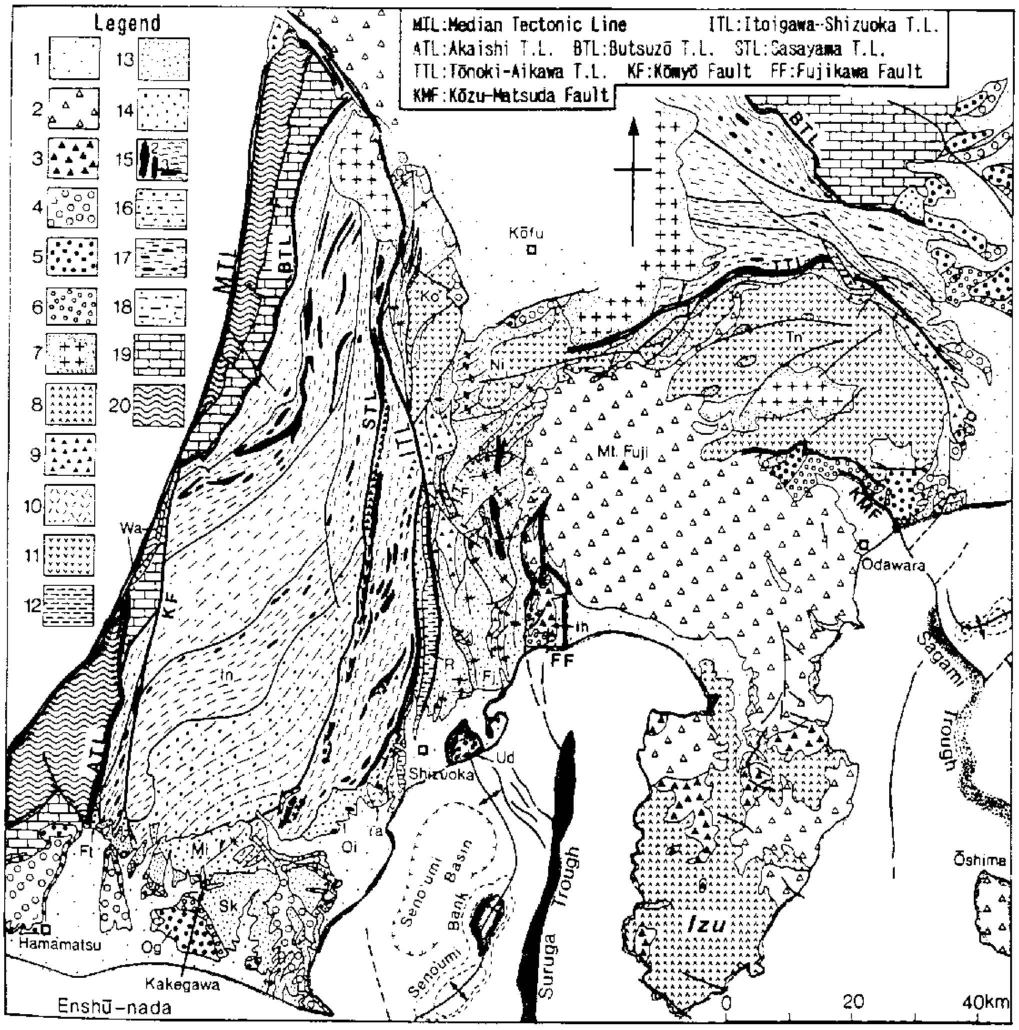


Figure 2. Geology and tectonics of Shizuoka prefecture

The sedimentary rocks sandwiched between Itoikawa-Shizuoka tectonic line (ISTL) and Median tectonic line (MTL) are heavily folded and the strikes of synclines and anticlines are almost NS, which implies that the region should had been subjected to high compressive forces in the geological past. The Izu peninsula, which is considered to be on Philippine Sea plate, has numerous short faults, whose strikes are generally

NW-SE. The well known other faults in the prefecture are Fujikawa-Iriyama fault, Tanna fault, Inatori fault and Irozaki fault.

Figure 3 shows the distribution of the sediments on the sea bottom in Suruga Bay (Ohta, 1983). The lower part of the continental slope along the trough axis is mostly occupied by the sedimentary rock covered with thin silt. In addition, cores taken along the main axis of the trough reveal a gravel bed below a level of 0.5 to 4.0 m from the bottom surface. Therefore, the distribution of the sediments in the Suruga Trough suggests the existence of strong currents in deep waters from the northern edge to the mouth of Suruga Bay along the trough axis.

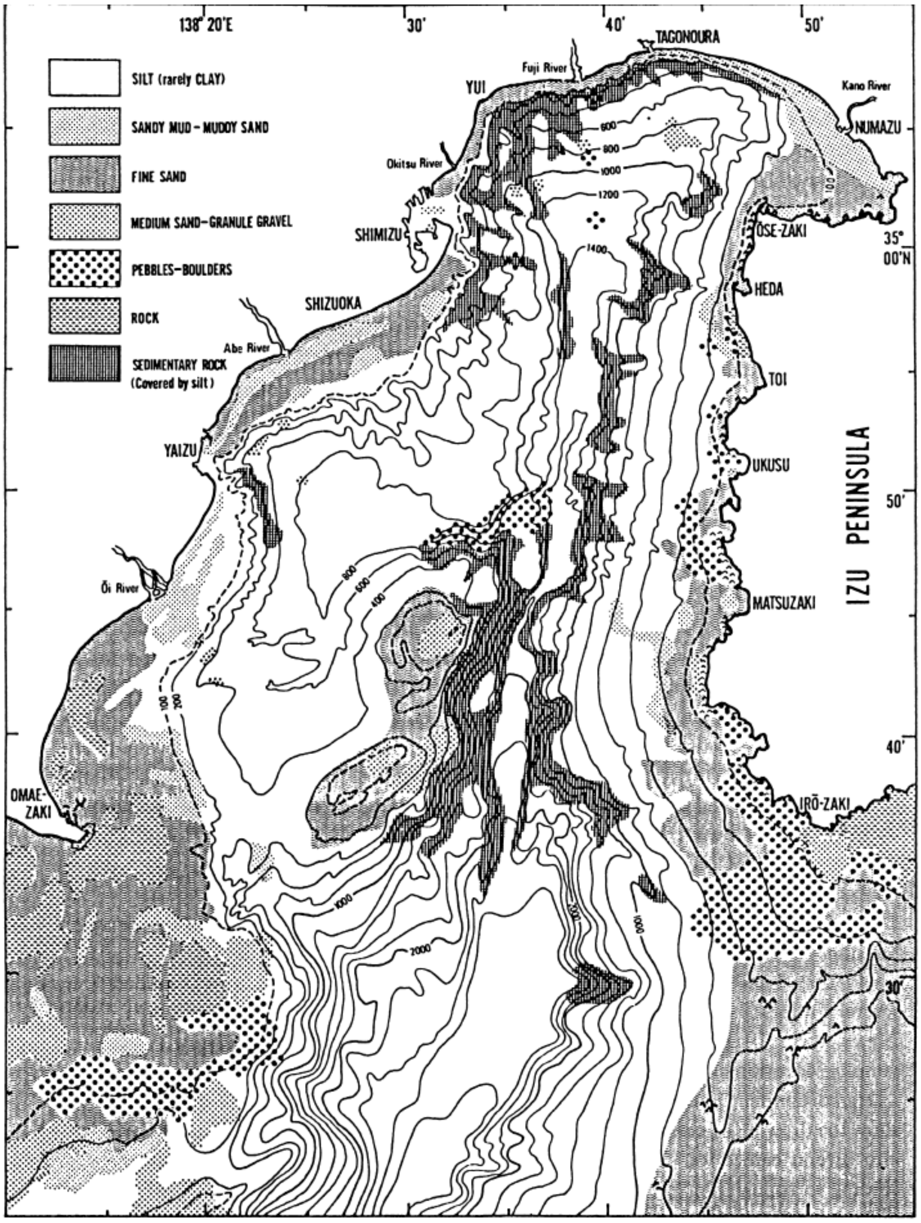


Figure 3. Distribution of sediments in Suruga Bay (from Ohta 1983)

4 TECTONICS AND CRUSTAL STRAINING

Shizuoka prefecture is a unique prefecture in Japan as several plate boundaries exist within the prefecture boundaries. Famous Mount Fuji appears to be at the junction point of these plate boundaries. There are four well-known tectonic lines, namely, Itoikawa-Shizuoka tectonic line, Sasayama tectonic line, Akaishi tectonic line and Median tectonic line. Itoikawa-Shizuoka tectonic line constitutes the southern boundary of Fossa Magna, which is considered to be the boundary between Eurasian plate and North American plate (Figure 4). Its strike is almost NS and its deformational sense is sinistral thrust type faulting. Sasayama and Akaishi tectonic lines are the boundaries of Shimanto belt, which consists of intercalated sandstone and shale. The Median tectonic line starts from Okinawa Through and terminates at the north of the prefecture by joining the Itoikawa-Shizuoka tectonic line. This tectonic line, which is more than 1000 km long, is considered to be associated with the interaction between Philippine Sea plate and Eurasian plate and it has the sense of dextral thrust type faulting.

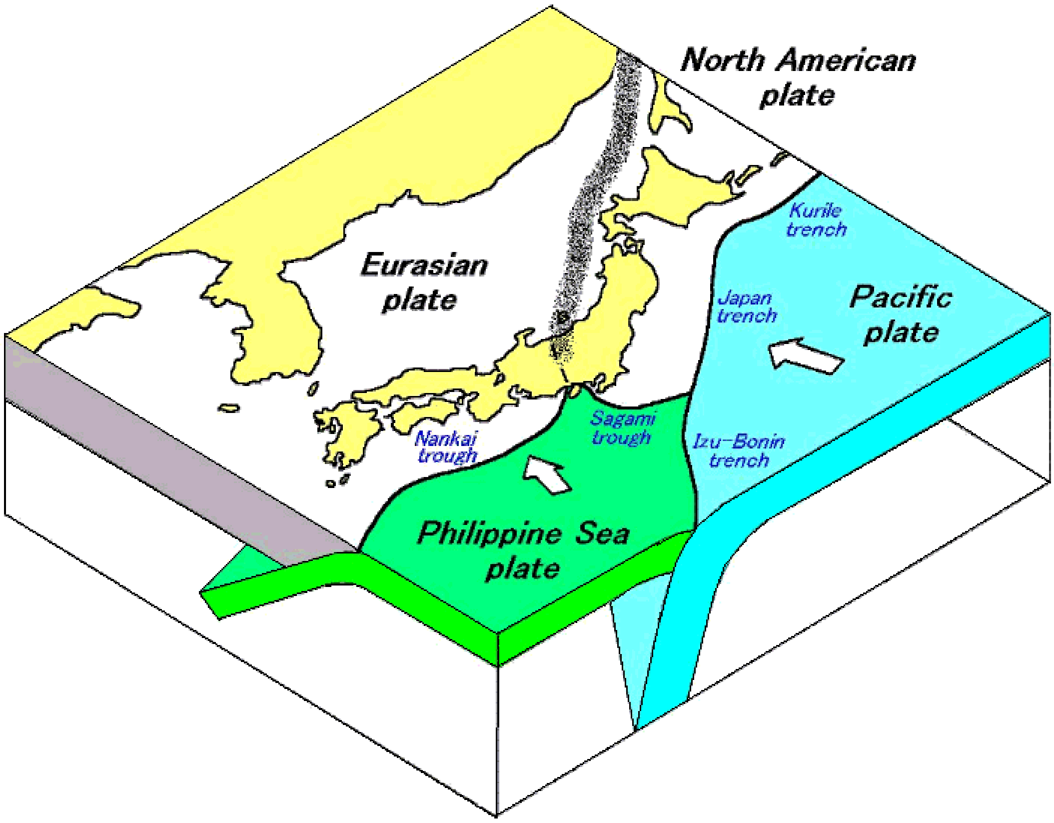


Figure 4: Tectonic structure of Archipelago of Japan

Except the Suruga Bay fault, the active fault map of Japan does not show any active fault in Suruga Bay where the earthquake occurred. However, the existence of a folding axis is noted in the north of the Senoumi basin as seen in Figure 2. Tsuneishi and Sugiyama (1978) studied the geology in the vicinity of Yaizu and they pointed out the possibility a new fault and named as Sunzu fault (Figure 5). This fault cut across the Suruga fault and extends to the Shirozaki fault at the southern tip of Izu Peninsula. The lateral component of this fault is dextral. Sea bottom topography is also consistent with this interpretation.

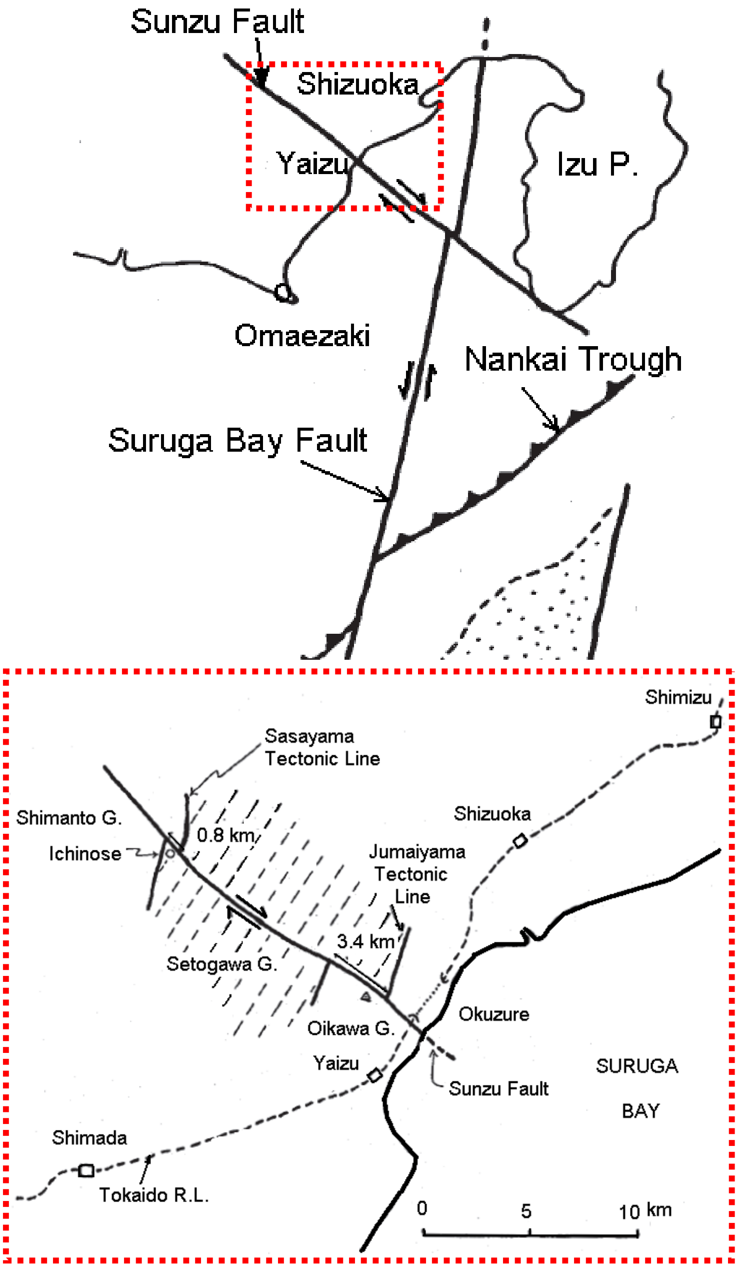


Figure 5: Faults in Suruga Bay (modified from Tsuneishi and Sugiyama, 1978)

Japan Geographical Survey Institute has been measuring crustal strains for about 100 years using the national triangulation system. This system has been recently improved by using the new continuous GPS technology. Figure 6 shows the maximum and minimum horizontal strain increments in the Central Japan for the period between 1883 and 1994. The compressive strains are aligned in the direction of NW-SE while the dominant direction of the extension strains is NE-SW. Nevertheless, strain regimes in Izu peninsula and its close vicinity is different from that in the western part of the prefecture. While the maximum compressive strains are almost in the direction of north-south in Izu peninsula they tend to become in the direction of east-west in the western part of the prefecture.

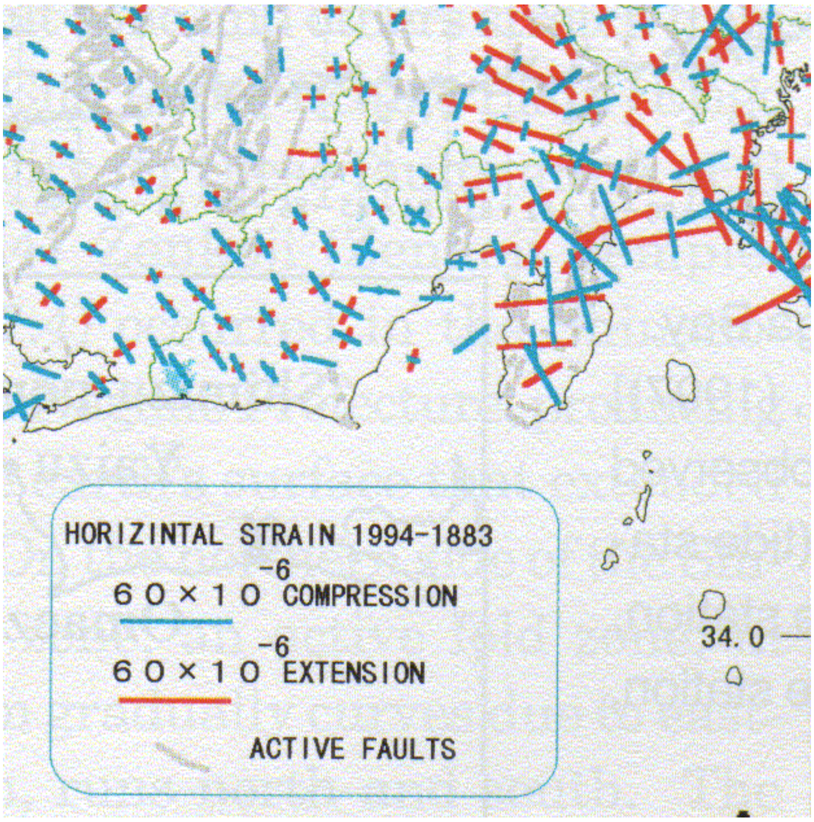


Figure 6. Crustal strain rates in the central Japan (after JGSI)

Largest crustal deformations observed in Japan take place in the Shizuoka prefecture and its close vicinity. Figure 7 shows the crustal deformation vectors in central Japan in the last 10 years. The measurements are from the GPS observation network of Japan.

Aydan (2006) have analyzed the crustal straining and changes of associated stress field in Tokai Region for the period between 1997 and 2005 using the data from GEONET GPS network operated by Japan Geographical Surveying Institute (GSI). Figures 8 and 9 show the changes of mean stress and maximum shear changes during the period of 1997 and 2005. Mean stress changes in the vicinity of Suruga Bay implies very high compression and they are elongated parallel to the axis of the Bay. The compression in Izu peninsula and the western shore of the Bay is remarkably high. Changes of maximum shear stress are also high in Izu Peninsula and the western shore of the Bay.

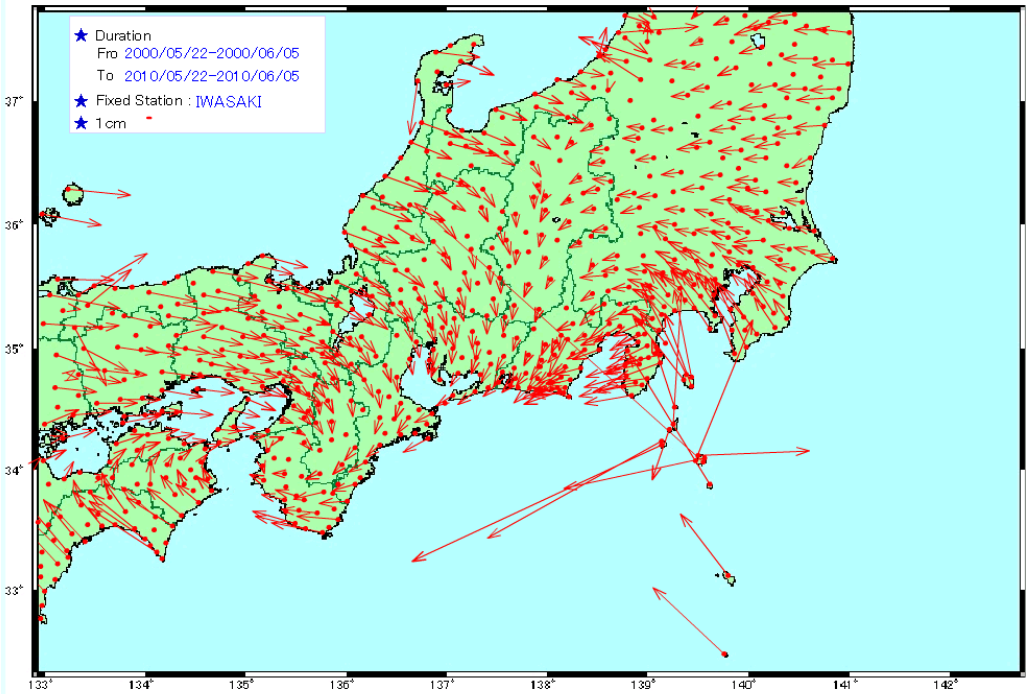


Figure 7: Deformation vectors for 10 years in Central Japan (from GSI, 2010)

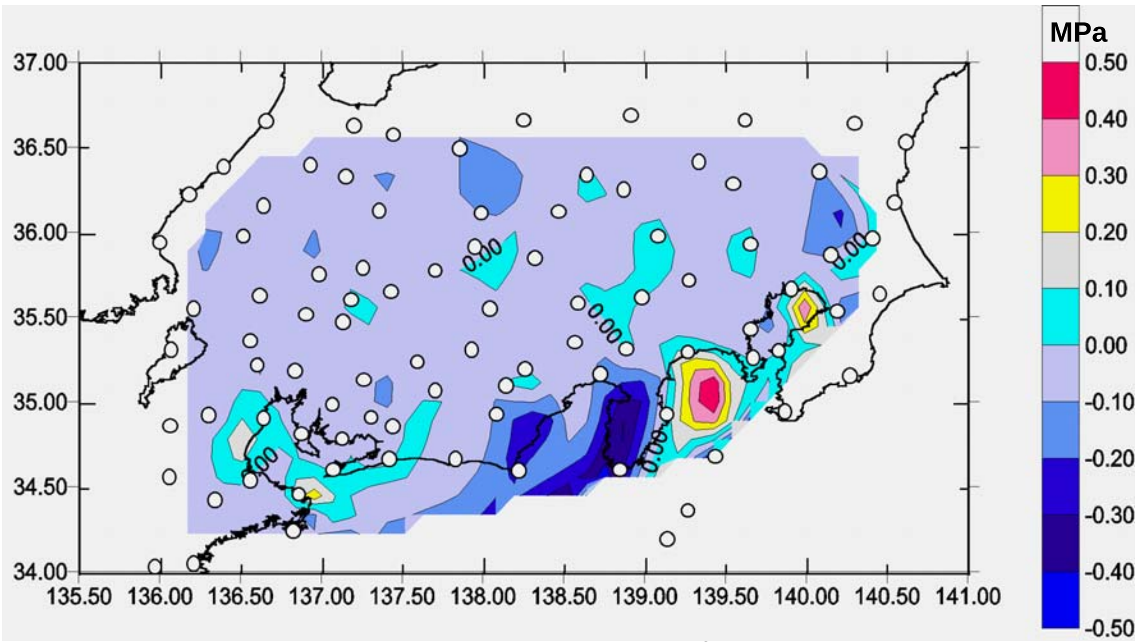


Figure 8: Mean stress variations between 1997 and 2005 (from Aydan, 2006)

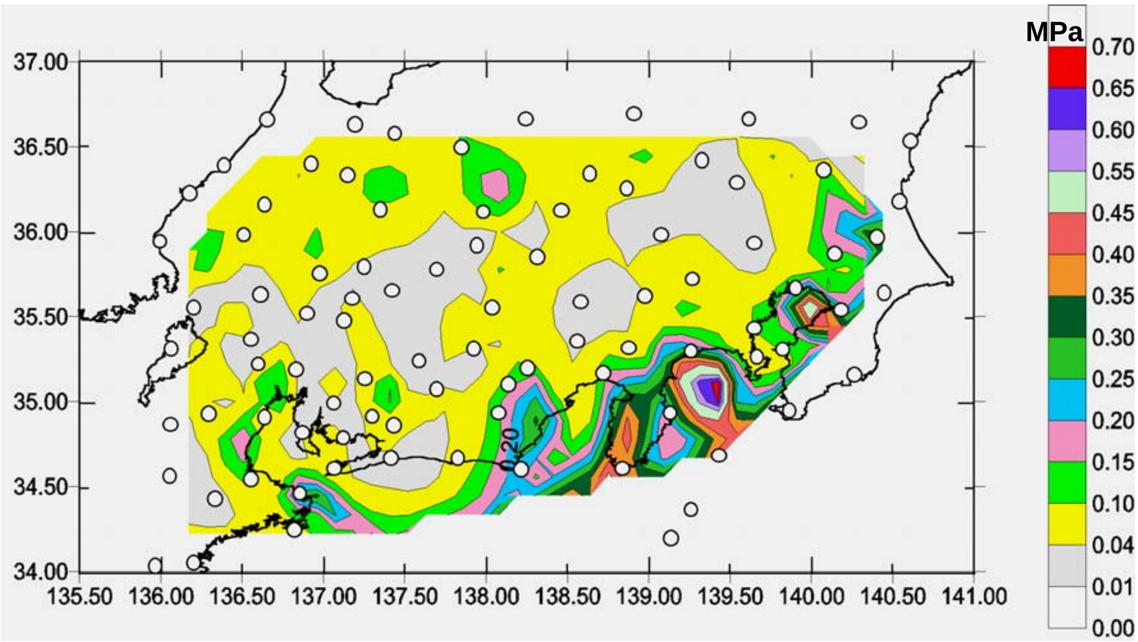


Figure 9: Maximum shear stress variations between 1997 and 2005 (from Aydan, 2006)

5 SEISMICITY AND FOCAL MECHANISMS OF PAST EARTHQUAKES

As Shizuoka prefecture is situated in the region where four major plates join together, it is seismically very active and the region produced very large earthquakes in the past. The hypocenter of the Tokai Earthquake anticipated since 1976 is considered to occur in the western part of the prefecture. Figure 10 shows the seismicity of the region between 1973 and 2010. The data used in the preparation of this figure obtained from the USGS database, which is publicly accessible. In the figure, the data along EW section and NS section were separately plotted as a function of the depth so that the plate subduction configuration can be inferred from the figures. The subduction of pacific plate (PAC) is easily recognized in the longitude-depth plot. The Philippine Sea Plate (PHP) is distinguished together with Pacific Plate. It seems that the PHP terminates at a depth of 150-200 km below the surface. The 2009 Suruga earthquake has been estimated to have occurred in the PHP. The epicentral area was seismically very quite and no foreshock occurred before the earthquake.

Noguchi (1998) studied the seismicity and focal mechanism of earthquakes in Tokai region. He separated the earthquakes into two groups namely upper plate earthquakes and lower plate earthquakes. The upper plate and lower plates in Tokai region are designated as Euro-Asian Plate and Philippine Sea Plate. The P-axes of the earthquakes in each group have entirely different orientations. While the upper-plate P-axes orientated EW while the lower plate P-axes orientated NS. Therefore the stress states in the Euro-Asian plate and Philippine Sea Plate should be entirely different from each other. This may imply that torsion-like force condition may exist in the vicinity of the interface of the Euro-Asian and Philippine Plates.

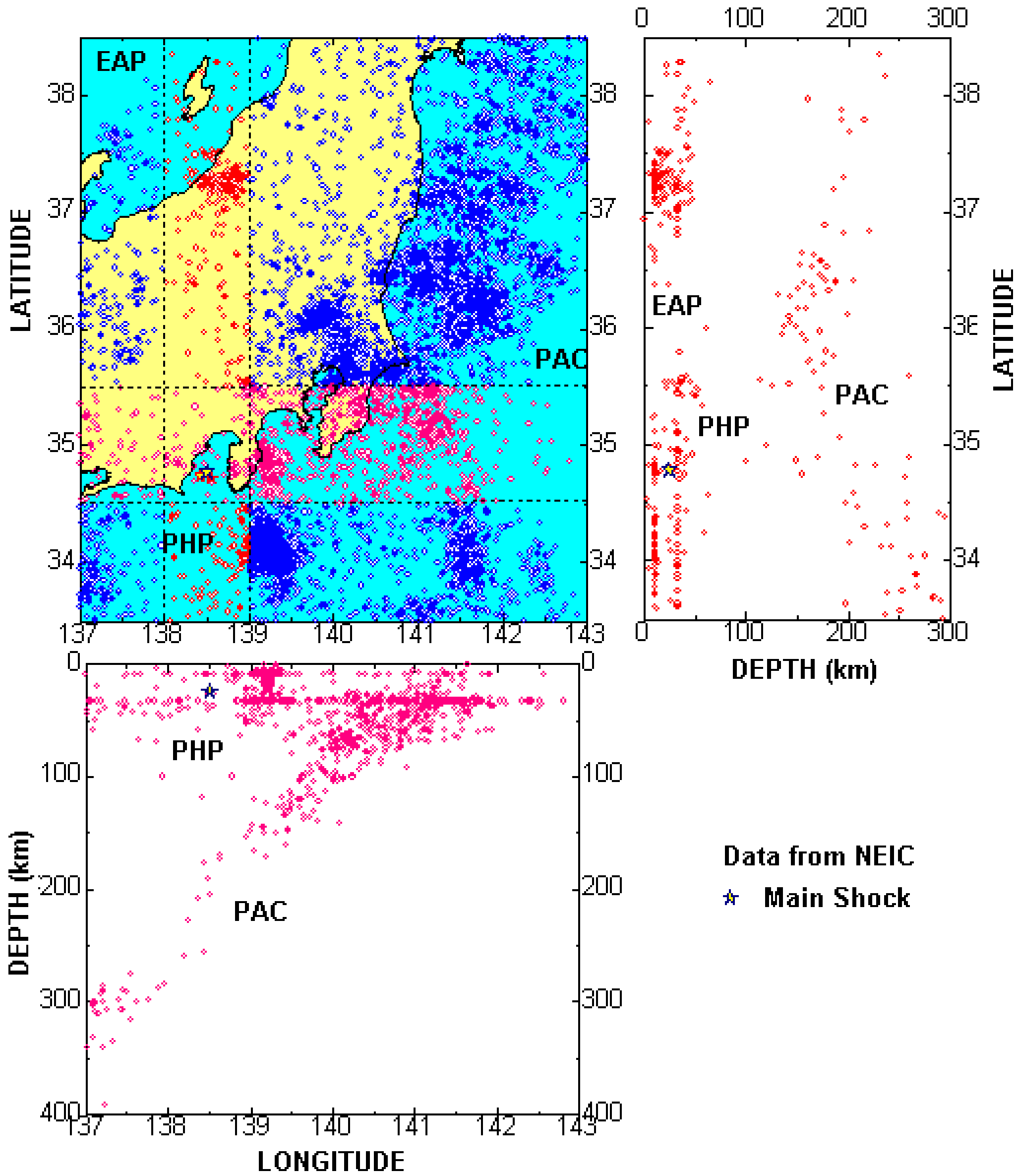


Figure 10: The seismicity of the epicentral area between 1973 and 2010.

Imanishi et al. (2009) processed the data of focal mechanism of earthquakes with a magnitude greater than 2.5 and hypocenter less than 60 km between 1979 and 2003. Their processed data is shown in Figure 11. The earthquakes in the east side of the Suruga Bay (Izu Peninsula) are either strike-slip type or thrust fault type. Their P-Axes are oriented in NS direction. As for the earthquakes in the western side of the Bay, the deep events are generally thrust fault type while the shallow events have a strike-slip or normal faulting mechanism. The P-axes of shallow events are almost in the direction of EW. This conclusion is similar to that of Noguchi (1998).

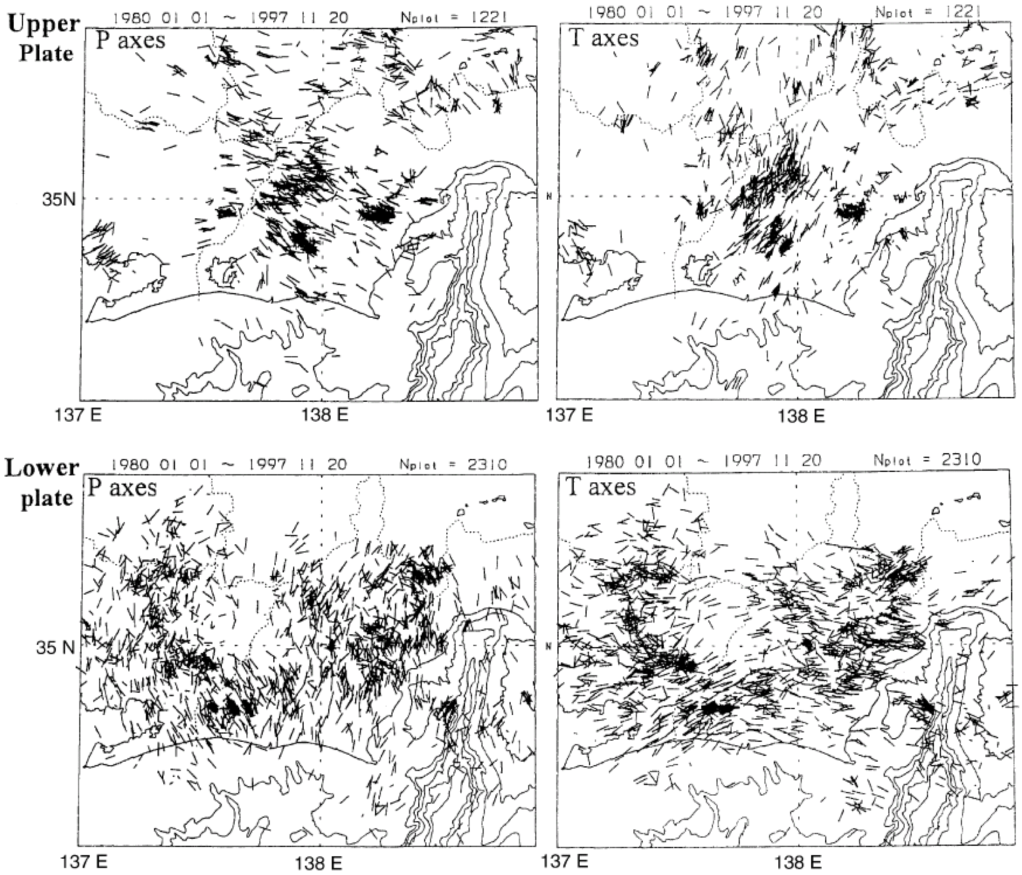


Figure 10: Orientations of P-axis and T-axis of earthquakes (from Nogouchi, 1998).

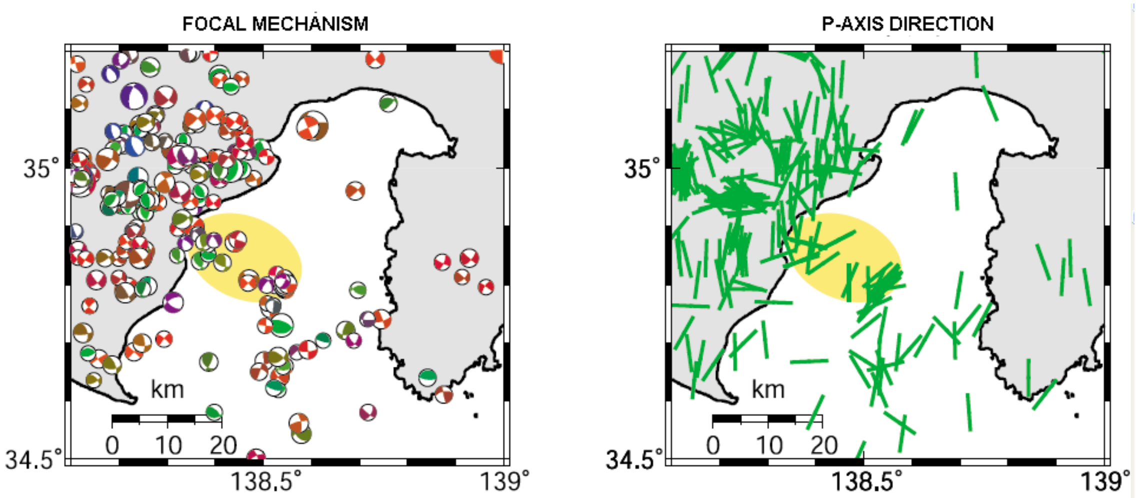


Figure 11: Focal mechanism and P-axis orientation of events between 1979 and 2003 (from Imanishi et al. 2009).

Aydan and Kim (2002) investigated the faults around Suruga Bay as shown in Figure 12. They reported possible focal mechanism of each fault and their stress field. The conclusion about the oirentation of P-axis and maximum horizontal stress direction was also similar to that of Noguchi (1998).

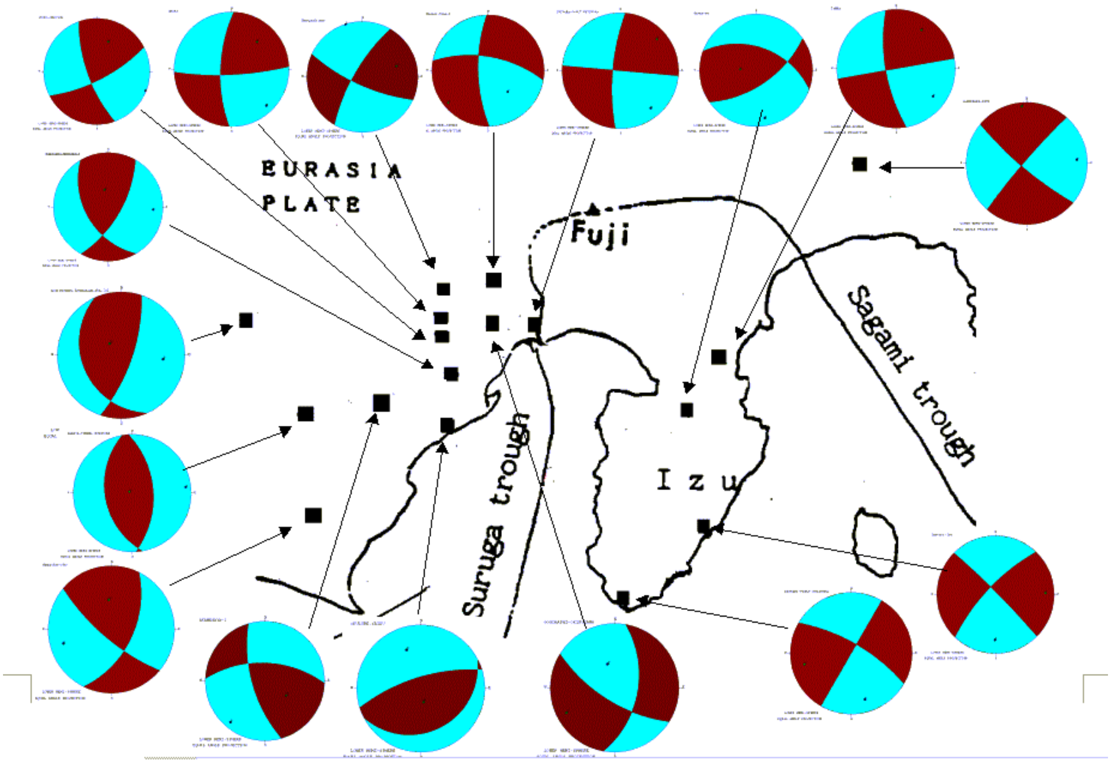


Figure 12: Inferred focal mechanism from the striations of the fault observations (from Aydan and Kim 2002).

6 SEISMIC CHARACTERISTICS OF MAIN SHOCK AND GROUND RUPTURES

The Suruga Bay earthquake occurred at 05:07, 11 August 2009 with a magnitude of 6.5 (Mj) (Mw 6.2) in the area of the anticipated Tokai earthquake according to the Japan Meteorological Agency (JMA). However, the hypocenter of the earthquake was inferred to be in the subducting Philippine Sea plate beneath Euro-Asia plate. Many institutes in Japan and abroad inferred the focal mechanism of the main shock as listed in Table 1. Although the solution provided by the NIED implies the rupture of two segments, the other solutions indicate a NE dipping fault plane caused the earthquake. The fault dimensions for this earthquake with a moment magnitude of 6.2-6.5 are expected to be 16-20 km long and 14-16 km wide with a relative slip of 55-60 cm (Aydan 2007).

The earthquake occurred on an unknown fault. The estimations indicated thrust faulting with dextral sense of deformation. However, it may correspond to Sunzu fault proposed by Tsuneishi and Sugiyama (1978) with the consideration of the sense of deformation and outcrop of faults in the vicinity of Okuzure region. The earthquake seems to have occurred within the subducting slab of the Philippine Sea Plate and the focal mechanism of the implied that it was due to thrust faulting, whose strike was perpendicular to that of the anticipated Tokai earthquake.

Table 1: Seismic parameters of the main shock of 2009 Suruga Bay Earthquake

Institute	Mw	Strike $(^o)$	Dip $(^o)$	Rake $(^o)$	Depth (km)	Length (km)	Width (km)	Duration (s)	Dmax (cm)
NGY	6.5	307	57	130	23	25	20	11	75
GSI	6.2	309	38	122	17.5	16.7	5.6		77
NIED	6.2	307	47	119	20	15	15		83
ERI-TU	6.1	322	49	135	14	22	16		
JMA	6.3	319	58	142	23				

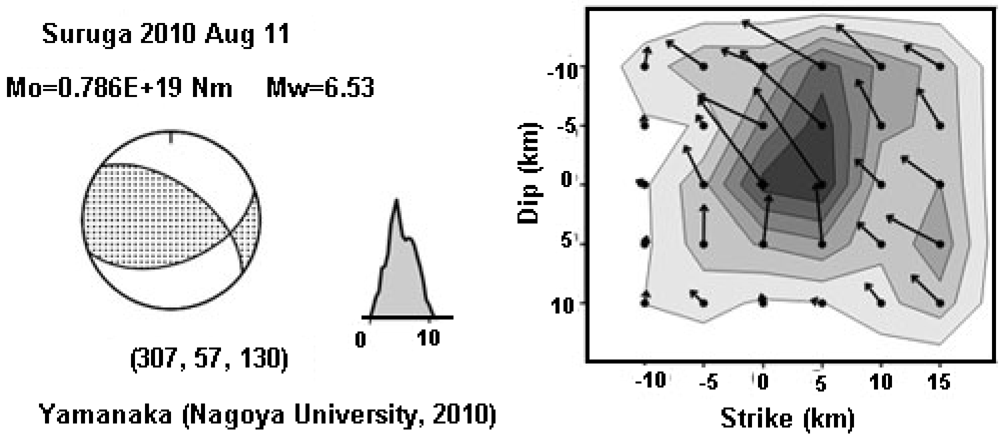


Figure 13: Focal mechanism, energy release and ultimate slip of the causative fault inferred by Yamanaka (2010).

The ultimate slip distribution obtained by Yamanaka (2010) is shown in Figure 13. Yamanaka (2010) estimated the maximum relative displacement to be about 75 cm for a moment magnitude of 6.53. Rupture duration is about 11 s and the ruptured fault length is about 25 km. As the rupture occurred below the sea level, there is no fault breaks reported in many post-earthquake investigations. However, the authors found some surface breaks at the Yaizu port, which is about 18.4 km away from the epicenter as shown in Figure 14. The surface breaks were perpendicular to the shoreline and they have the dextral sense of deformation with sand boiling. The northern side of the wavebreak in the port moved upward while the southern side downward. Considering the estimated length of the causative fault and sense of the horizontal offset, it is very likely that the ground breaks observed in the Yaizu port may be caused by the causative fault. Furthermore, the first author observed similar type ground ruptures with sand boiling during the 1999 Düzce earthquake (Aydan et al. 2000).

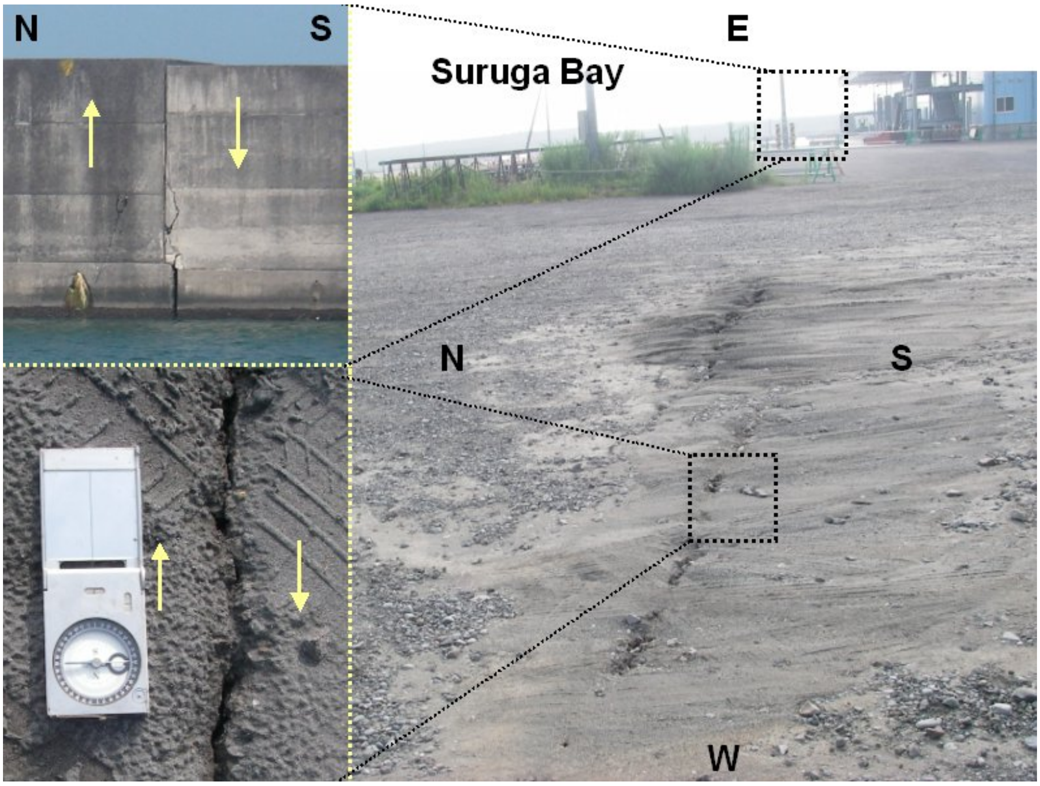


Figure 14: Surface ruptures and deformations observed in Yaizu port

7 STRONG MOTIONS

Very high ground accelerations were recorded during this earthquake. The Omaezaki strong motion station of the Japan Metoreological Agency (JMA) recorded the highest ground acceleration. However, this strong motion is just on top of the thin strip of ground with an elevation of 46 m. In addition to Omaezaki strong motion record, very high ground accelerations were measured at Minami Shizuoka and Shuzenji strong motion stations of KIK-NET. However, the high strong motion records are greatly affected by the peculiar ground topography in the vicinity of these strong motion stations. Figure 15 shows records of the several strong motion stations around Suruga Bay and their acceleration response spectra are shown in Figure 15. The dominant spectral period ranges between 0.3-0.4 seconds and long period components were observed in the records of Shimizu, Haibara and Numazu strong motion stations. This may be due to the existence of thick sedimentary deposits at these localities.

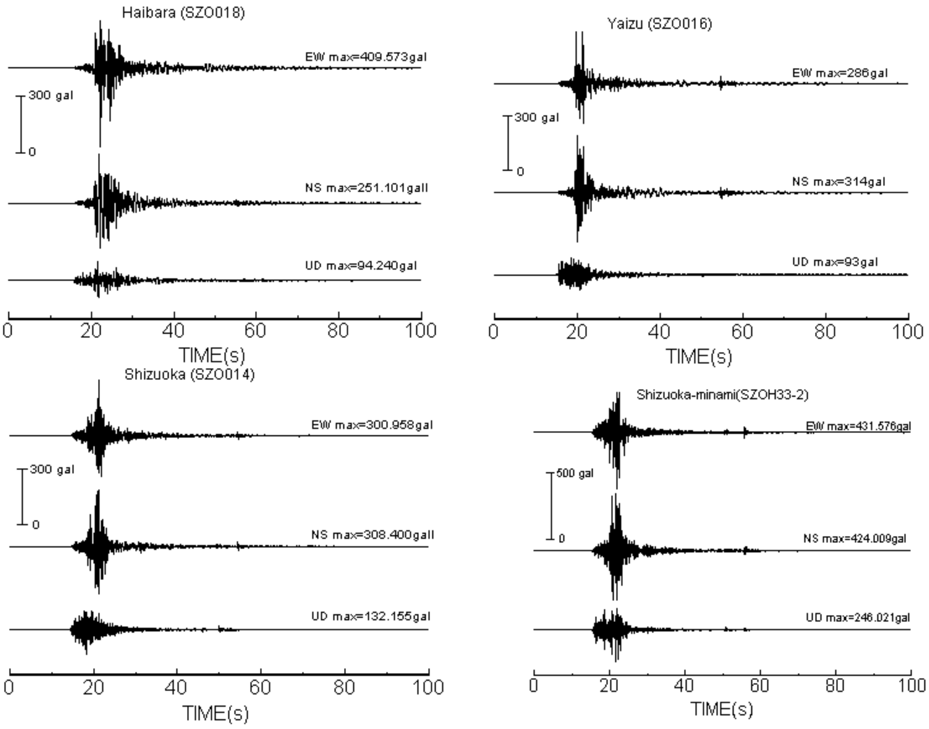


Figure 15: Acceleration records at several strong motion stations of K-NET & KIK-NET

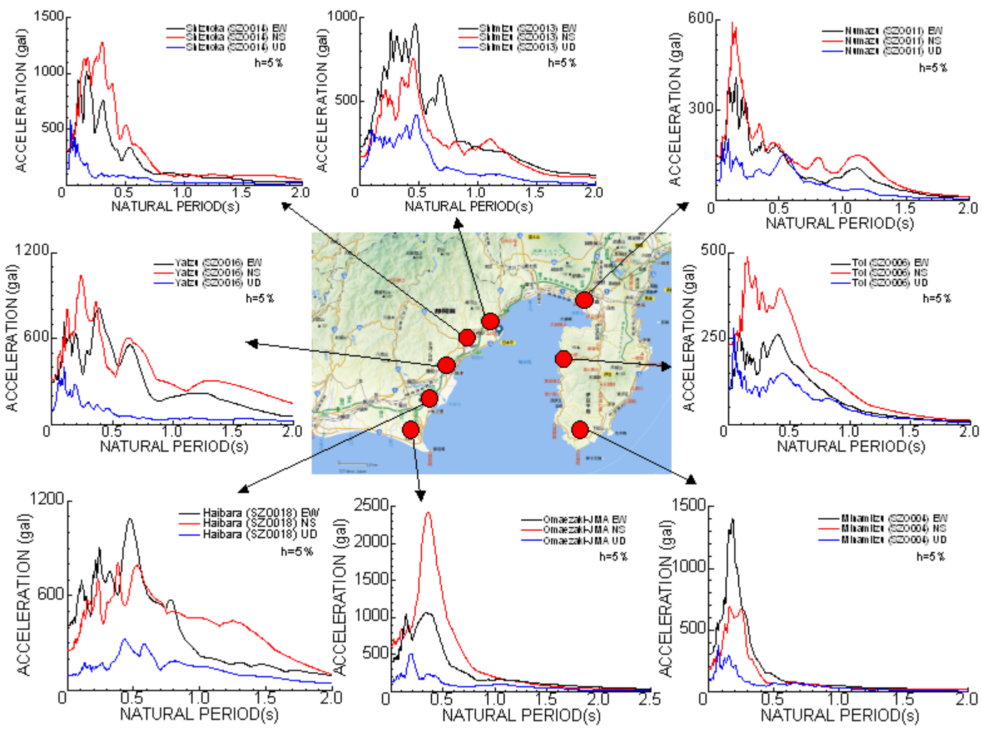


Figure 16: Response spectra of acceleration records around Suruga Bay

Figure 17 shows the attenuation of maximum ground acceleration. The data from K-NET and KIK-NET strong motion networks are generally in agreement of the existing attenuation relations while the data from the network of the Japan Meteorological Agency (JMA) are generally high. The sites operated by the JMA may also be affected by their environmental conditions and they may not be representing the free-field ground motions as they are housed either in or next to the buildings. The acceleration records of K-NET and IK-NET are more representative of the free-field responses. The data from K-NET, KIK-NET and JMA indicates that the vertical ground accelerations are generally 0.4 times the horizontal ground acceleration as seen in Figure 18.

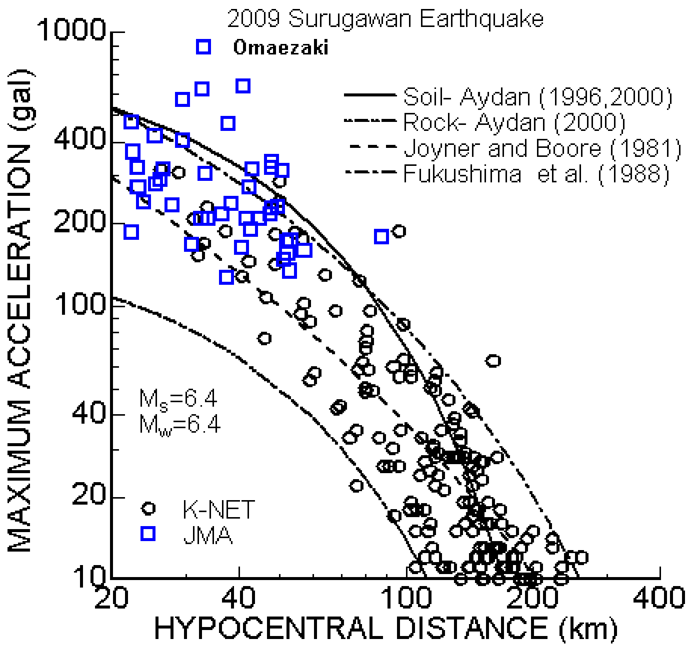


Figure 17: Attenuation of maximum ground acceleration

The maximum ground acceleration contours using the data of K-NET and KIK-NET are shown in Figure 19. As there is no data in the Suruga Bay, the contours become somewhat biased. Figure 20 and 21 shows the maximum ground acceleration and maximum ground velocity distribution estimated from the empirical relations proposed for interplate earthquakes by Aydan and Ohta (2006). If the intra-plate relations are used they rapidly attenuates and they can not evaluate the distributions shown in Figure 19. The distributions for a surface ground having shear velocity of 300 m/s are similar to those shown in Figure 19. The deviation is due to the difference between actual shear wave velocity as well as topographical effects. The estimated maximum ground velocity is about 40 kine and this value is in accordance with observed values. As the ground velocity was generally low, this may be explain why the damage was light.

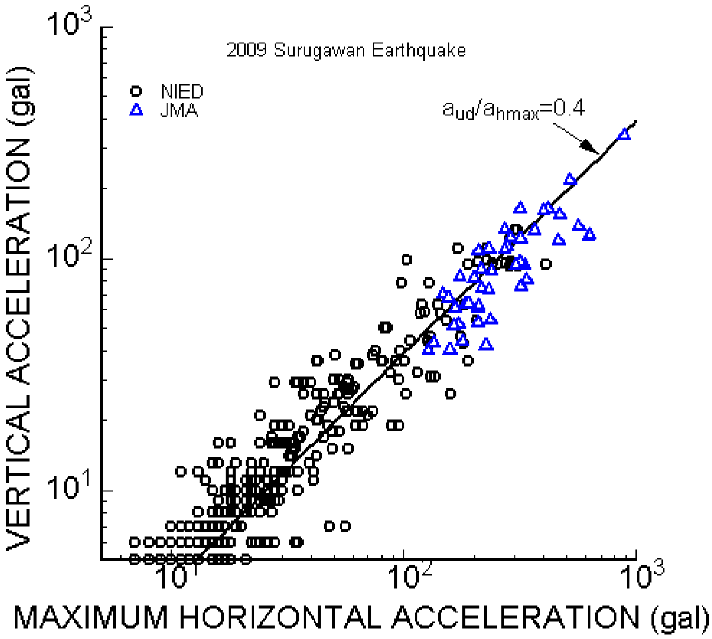


Figure 18: Relation between vertical acceleration and maximum horizontal acceleration

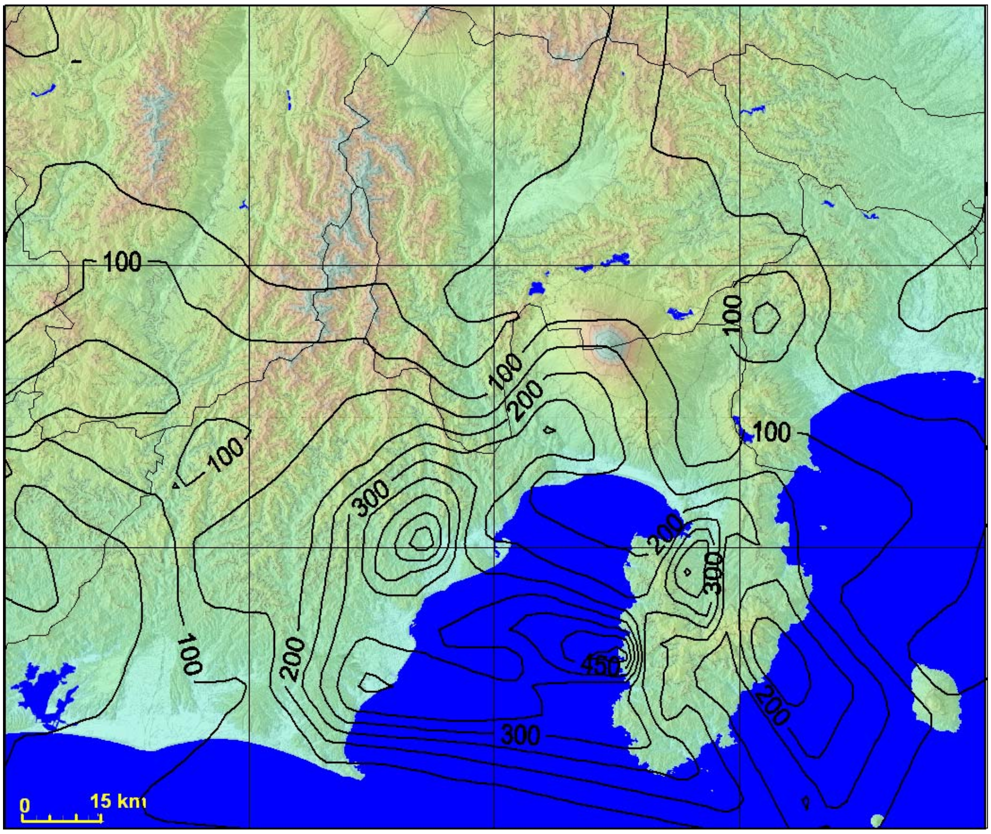


Figure 19: Contours of maximum horizontal acceleration obtained from K-NET and KIK-NET strong motion networks.

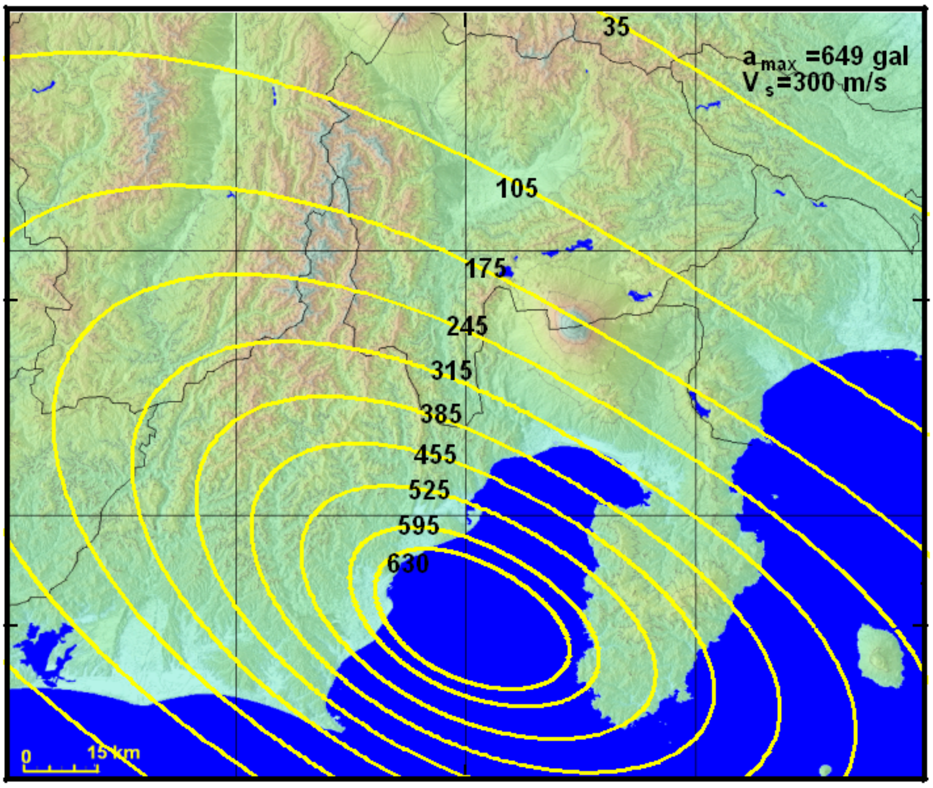


Figure 20: Maximum horizontal ground acceleration contours

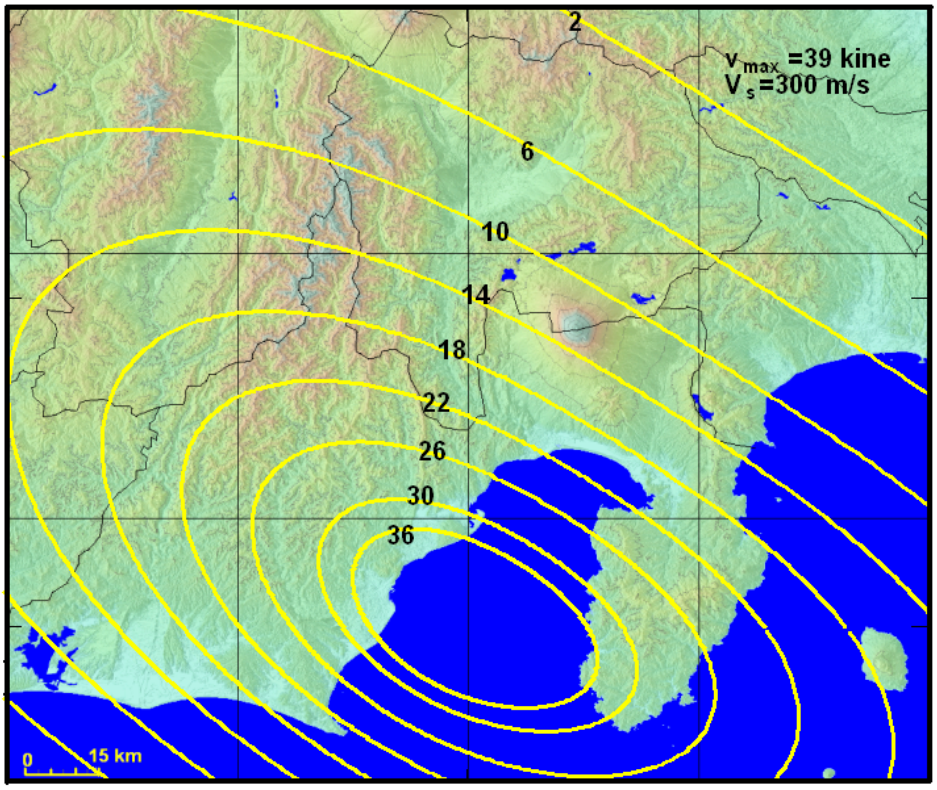


Figure 21: Maximum horizontal ground velocity contours

8. STRUCTURAL DAMAGE

8.1 Building Damage

There was no collapse of buildings caused by this earthquake. The damage to buildings was mainly limited to the roofs of the common two story buildings. High-rise buildings are fundamentally steel structure with extra reinforced concrete columns and shear walls. Low-rise buildings are generally reinforced concrete buildings. The damage was particularly widespread in the vicinity of Haibara and areas with soft-ground conditions. The tiles of roofs were displaced due to ground shaking and fallen subsequently as seen in Figure 22:

(a) Yaizu masonry building

(b) Yaizu

(c) Makinohara SA

(d) Uchinomaki-Shizuoka

(e) Omaezaki

(f) Oikawa

(g) Haibara

(h) Heda

Figure 22: Damage to two-story buildings in the earthquake affected area

There is no report of damage to high-rise buildings including one of the compounds of Shizuoka Prefectural government buildings. Reinforced concrete buildings performed well during the earthquake. Some reinforced concrete buildings in liquefied areas were also cracked (Figure 23(a,b,d)). Retrofitted RC buildings also performed well. However, there were some cracking in unretrofitted floors of such buildings (Figure 23(c)).

(a) Yaizu Deep-sea water facility

(b) Sagara-Sakai fishing port building

(c) Cracking in the unretrofitted floor of a retrofitted building

(d) Yaizu port

Figure 23: Slight damage in reinforced concrete buildings

8.2 Damage to Temples, Shrines and Cemeteries

Damage to temples and shrines generally occur at gates and buildings. The gates of temples are either made of granitic stone or wood. Furthemore, damage to monuments and stone lanterns occur along the alleys leading to the main compound. The damage to such structures occurred in temples and shrines situated over soft ground or hilly ground with ridges (Figure 24). The damage to main buildings and auxiliary structures were mainly due to the displacement of roof tiles and/or the relative sliding of the wooden columns over the foundation stones. In some of temples and shrines, uneven settlement of ground due to liquefaction caused some distressing in the main buildings.

(a) Aishoden – West Shizuoka

(b) Yaizu

(c) Sagara

(d) Yaizu

(e) Sagara

Figure 24: Damage to temples and shrines

The damage to cemeteries were very extensive particularly in areas with thick soft sedimentary ground. Tombs in cemeteries consist of well-shaped stone blocks, which mostly have rectangular prism shapes.

(a) Sagara

(b) Shuzenji

(c) Shuzenji

(d) Sagara

(e) Shuzenji

(f) Shuzenji

Figure 25: Damage to tombs of cemeteries

The collapse direction and collapse ratios of the stones of tombs served as a measure of intensity of shaking since early times in Japan. In earlier tombs, no bonding agent has been used. However, the use of stone dowels is generally common. In recent tombs, some bonding agents and/or steel dowels are used. When all resistance is due to frictional forces, they are well indicators of the ground motions. When the resistance depends on either frictional and/or geometrical shape, the failure modes are sliding, toppling or combined sliding and toppling with or without rotation (Figure 25). In some cases, there were failure of ground or retaining walls in cemeteries on hilly ground.

8.3 Damage to Suspended Ceilings of Halls or Sport Facilities

Hall and Sport facilities have different forms of suspended ceilings. Aydan et al. (2007) reported some examples of ceiling falls of pools and restaurants occurred during the Kameyama earthquake, which is a small size earthquake (M5.2) and pointed out the secondary disastrous effects of such falls. The fall of panels of ceiling occurred in indoor pools and gymnasium halls in Shizuoka (Figure 26). Furthermore, the fall of lights also occurred. As the earthquake occurred in around 5 AM in the morning, there were luckily no injuries or casualties. However, this is a very serious issue and it has to be quickly addressed.

Figure 26: Fall of panels from the roof of swimming pools in Shizuoka

8.4 Damage to Glass-roofs or Show Windows

Another form of non-structural damage is the breakage of glasses of show windows, windows of buildings and glass panels. Figure 27 shows several examples of the breakage of the glass windows. When glasses have covered with transparent films or a contain wire mesh, their behavior becomes more ductile upon fracturing.

Similarly aquariums made of glass or acrylic were either cracked, which resulted in some leakage of water.

Figure 27: Examples of fractured or broken glasses of windows and aquarium

8.5 Damage to Walls, Shelves and Non-Fixed Objects

Walls are generally vulnerable to topple due to high aspect ratio of their height to width. Although it is an obligation to put reinforcing bars in brick walls, they may fail under strong shaking. When they fail by toppling, they behave like a monolithic body. Such failures may be more dangerous compared to those without reinforcing bars. Figure 29 shows several examples of wall failure in the epicentral area.

(a) Yaizu

(b) Sagara

Figure 28: Toppling of walls

Many shops, particularly convenience shops, have shelves with goods. It is now a common phenomenon to see many goods fallen or displaced from the shelves in such shops due to earthquakes. Figure 30 shows several examples of damage in some convenience shops.

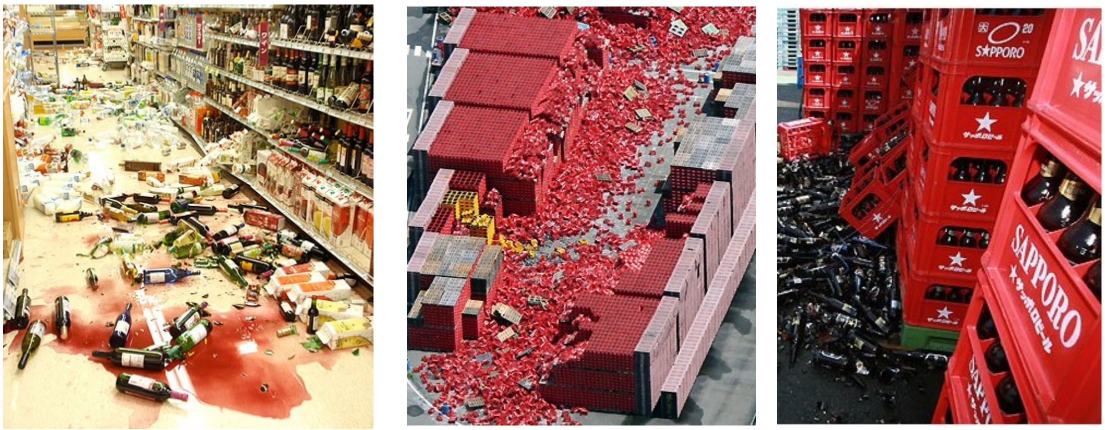


Figure 30: Views of fallen or toppled goods (pictures collected from newspapers)

Figure 31 shows several views of toppled non-fixed objects in Kusanagi and Orido of Shimizu Ward of Shizuoka City. The toppling or deformation of non-fixed objects occurred particularly in N-S direction, which clearly indicated a very strong directivity effect of ground motions. These locations are on the hanging wall side of the causative earthquake fault.

Figure 31: Toppling of non-fixed objects

9 GEOTECHNICAL DAMAGE

9.1 Embankments

The earthquake caused the settlement, partial sliding or complete sliding of embankments of roadways and riverbanks. Figure 32 shows several examples of embankment damage.

(a) The repair of the tight bank of Abe River in Shizuoka City

(b) Route 59 (Izu Peninsula) (c) Near Kikugawa

Figure 32: Some examples of embankment damage

The most spectacular embankment damage occurred on the TOMEI expressway at the point of KP191.6 near Makinohara Service Area (Figure 33). A 40 m long section of the highway slipped towards north. As this expressway connects Tokyo and Osaka and it was the most important religious holiday in Japan, tremendous efforts were done for the quick repairment of the expressway. It was re-open to traffic after 5 days. As No 9 typhoon passed over the area before the earthquake, it was expected that the ground water level raised resulting in the most vulnerable state for the failure of the embankment during a strong shaking. The embankment was 28 m high an it was built about 50 years ago. The maximum ground accelerations were 488 gals at Kikugawa Interchange (10.2 km away from failure location) and 424 gals at Haibara. Figure 34 shows the pre and post failure configuration of the embankment.

(a) Areal view of the failure (modified Japan Geographical Surveying Institute)

(b) A view of the fully restored embankment (picture on July 1, 2010)

Figure 33: Views of the failed embankment before and after restoration

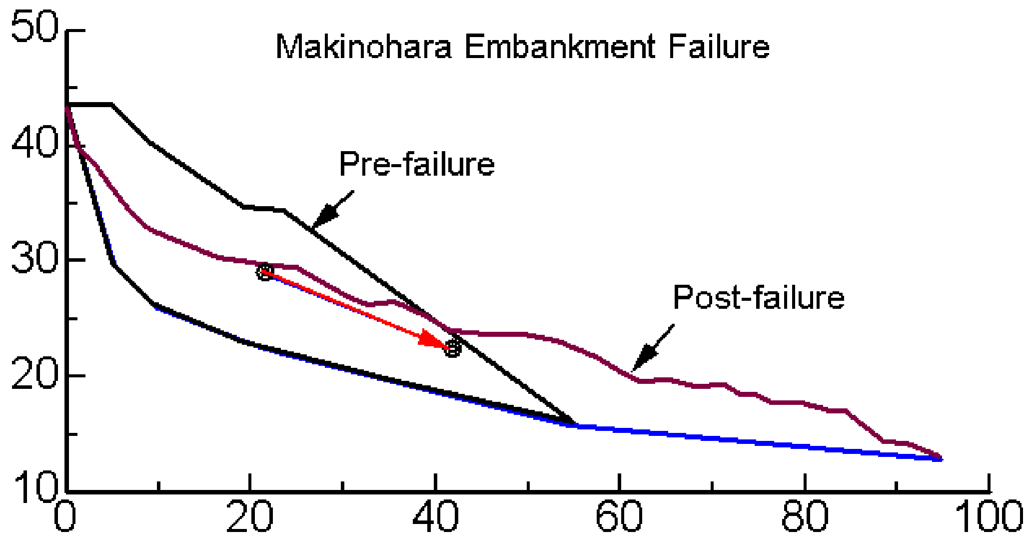


Figure 34: Pre-post configuration of the embankment

9.2 Retaining Walls

There are different types of retaining walls. Old retaining walls are generally of dry masonry type. Stones used are either rounded or cut to rectangular prism shape and the size changes depending upon their height, location and purpose. Some of recent retaining walls were constructed using the pre-cast concrete blocks. The inclination of the retaining walls generally ranges between 70^o and 80^o. The failures were generally induced by the displacement of a stone or several stones in the wall, which serves a point of singularity to induce the failure of subsequent fall of stones (Figure 35). The dry masonry retaining walls having rounded stones are more vulnerable to failure during the earthquake. Although the retaining wall on the northern side of the Makinohara service are did not collapse, there was a trough-going crack in the retaining wall, which may be caused by a mass-movement or ground rupture.

The most publicized retaining wall failure was observed at the remains of the Sunpu Castle (Figure 36). The retaining walls of about 8-9 m high failed at three locations in N-S direction, indicating the directivity effect of the strong ground motions. Two failures occurred at the south and north side of the outer moat (soto-bori) and one failure occurred in the south side of the inner moat (uchi-bori). The size of corner stones is generally large (longest side length is about 200 cm) and placed in an intermittent pattern with an average inclination of 70^o. The sizes of blocks at other parts are very variable. Nevertheless the longest side of the stones cut into pyramid shape is generally more than 80 cm and it is placed into the inside of the wall (Figure 37). Old stones are generally made of andesite and porphrite while the newly restored parts consist of basalt blocks. It is well known that the retaining walls suffered heavy damage in the past. It is reported that all retaining walls were collapsed during the 1854 Ansei earthquake. Some part of the restored retaining wall failed again in the 1935 Shizuoka earthquake. Although the configuration of the retaining walls of Japanese castles is earthquake-resistant, the ground motions are generally expected to be large to fail these retaining walls.

(a) Izu

(b) Uchinomaki-Shizuoka

(c) Koseto-Shizuoka

(d) Banjou-Water fall – Izu

(e) Makinohara Service Area

Figure 35: Some examples of retaining wall failure

The inspection of the failed retaining walls indicated rounded sandstone and shale gravels used as backfill material except the soil for growing plants on the top of the retaining wall. The first author also noticed some bulging in retaining walls during 2008. As the average inclination of retaining walls was about 70^{o}, it was unlikely for the walls to fail in rotational mode on the basis of previous case histories and analyses (Aydan et al. 2008). The fundamental mode of failure is likely to be the inter-sliding of blocks, which has a pyramid shape under strong shaking in N-S direction. The bulging of the wall probably rotates castle wall blocks and loosen the contact between the load carrying blocks and small filling stones or gravels. Round large river gravels seem to be used as the back-fill material, which probably reduces the apparent friction of the back-fill material. This, in turn, results in the increase of the pressure from the back-fill material on the retaining walls.

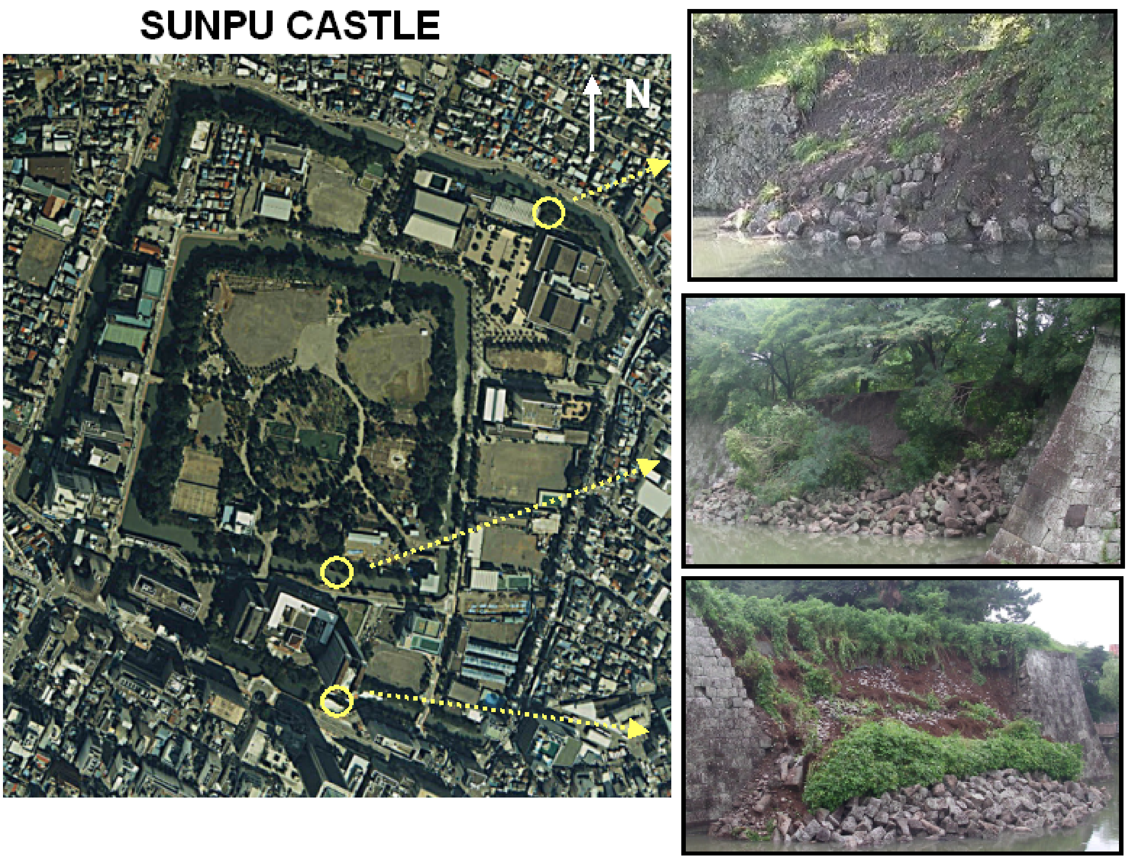


Figure 36: An aerial view of Sunpu castle and views of failed retaining walls

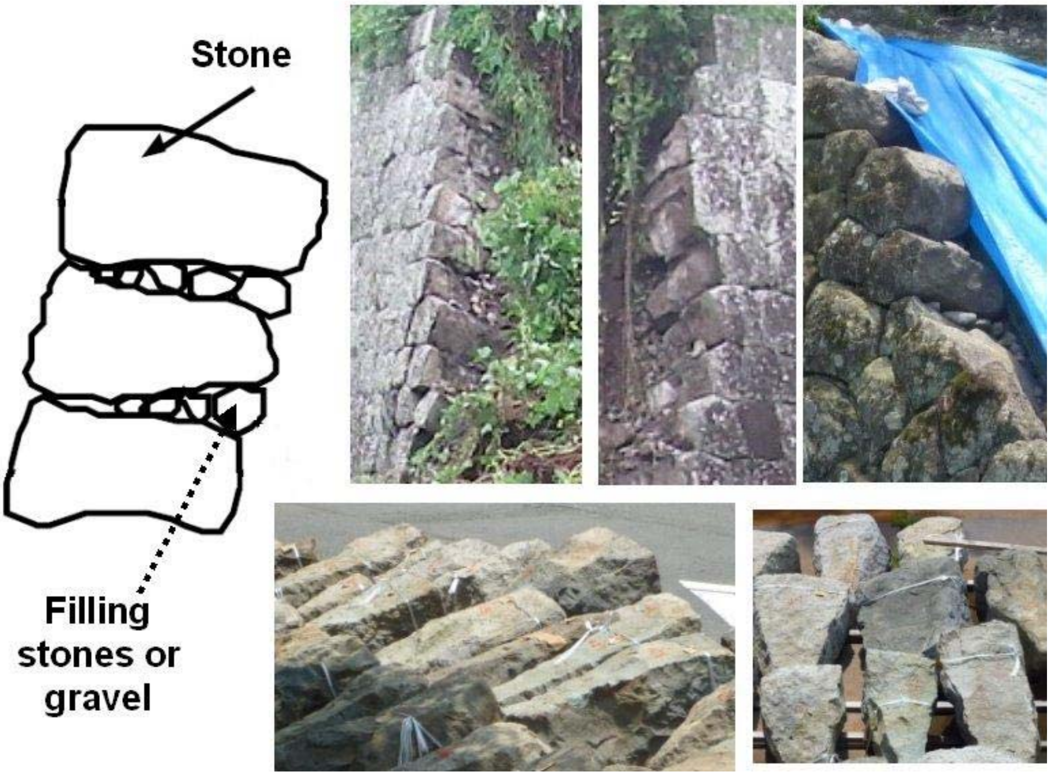


Figure 37: Masonry technique for building retaining and castle walls of Japan and views of stones used in Sunpu castle retaining walls.

9.3 Slope Failures

Shizuoka is one of the mountainous prefectures in Japan and there are very large-scale rock slope failures. For example, the 1707 Hoei earthquake caused the Oya-kuzure failure. Another area is called Yui, where slope failures occurred and resulted in the disruption of railway and roadway between Tokyo and Osaka in 1970s. The Okuzure shore is another area of the huge slope failures and it was the main route between Tokyo and Osaka before the construction of Nihonzaka tunnels. One can find the remains of the collapsed tunnels of the old Tokaido railway tunnel (Figure 38).

The authors inspected slope failures in the areas of Okuzure, Yui and along the banks of Abe River as far as Umegashima hot-spring area. Rock masses along Abe river are generally intercalated steeply dipping sandstone and shale, which are very prone to fail in flexural toppling mode. However, there are some porphrite dykes from place to place. Rock masses of the Yui landslide area are sandstone with mudstone as well as tuffacous rocks. The layers of jointed sandstone generally dip into mountainside, which may make them vulnerable to either toppling failure and/or wedge failure. Rock masses of

Okuzure are volcanic and consist of andesite and basalt with columnar joints. Furthermore, the rock mass is disturbed by thrust faults and strike-slip faults.

Figure 38: The remains of the tunnel of the old Tokaido railway line

The earthquake caused numerous slope failures and rockfalls of various scale along the banks of Abe River as far as Umegashima area, Yui, Okuzure and the west shore of Izu Peninsula (Figure 39). As most of slope failures far from the populated areas and involved natural slopes, their effect was minimal. However, it was interesting to note that the slope failures occurred in previously known locations of slope failures. This may further imply that larger earthquakes may cause significant slope failures, which may have significant effects in the prefecture. Slope failures may be classified as surfacial sliding, planar or wedge sliding and toppling depending upon the slope configuration and discontinuities in rock masses.

The author compiled slope failures caused by the 2009 earthquakes according to Keefer's classifications and plotted in Figure 40. Besides the empirical bounds of Keefer, the empirical equations proposed by Aydan (Aydan 2007, Aydan et al. 2009) are also plotted in Figure 40. The observations on the slope failures caused by the 2009 Suruga Bay earthquake fall within the empirical bounds of Aydan's relations.

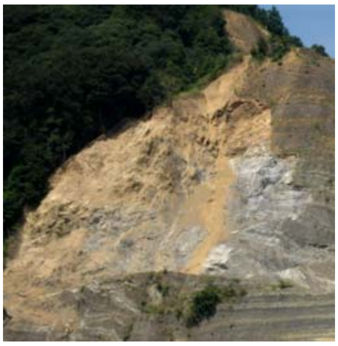

(a) Surfacial slope failures along Abe River

(b) Slope failure on Route 17

(c) Yui

(d) Abegawa

(e) Umegashima



(f) Abegawa

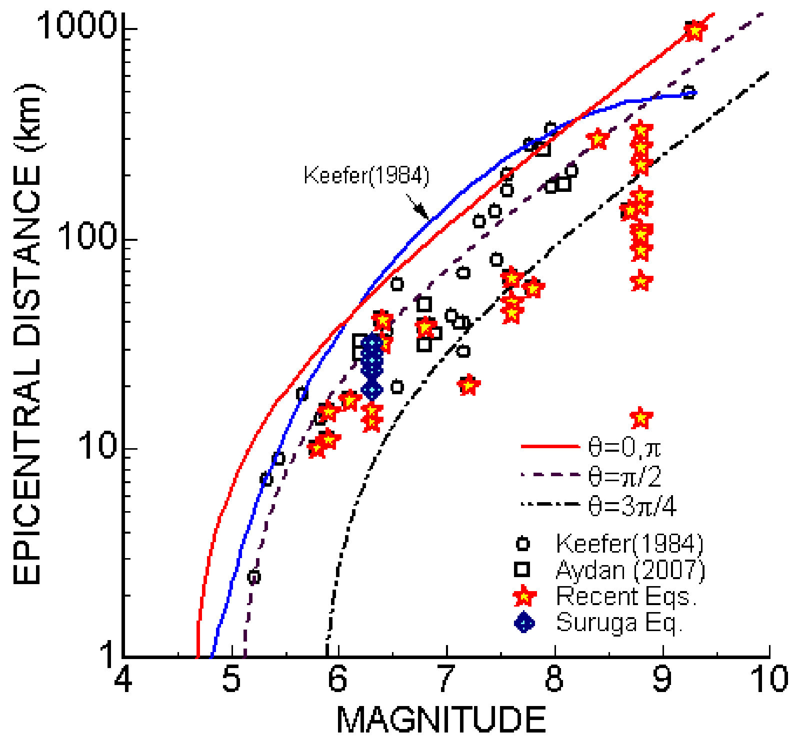
(g) Okuzure

(h) Toi

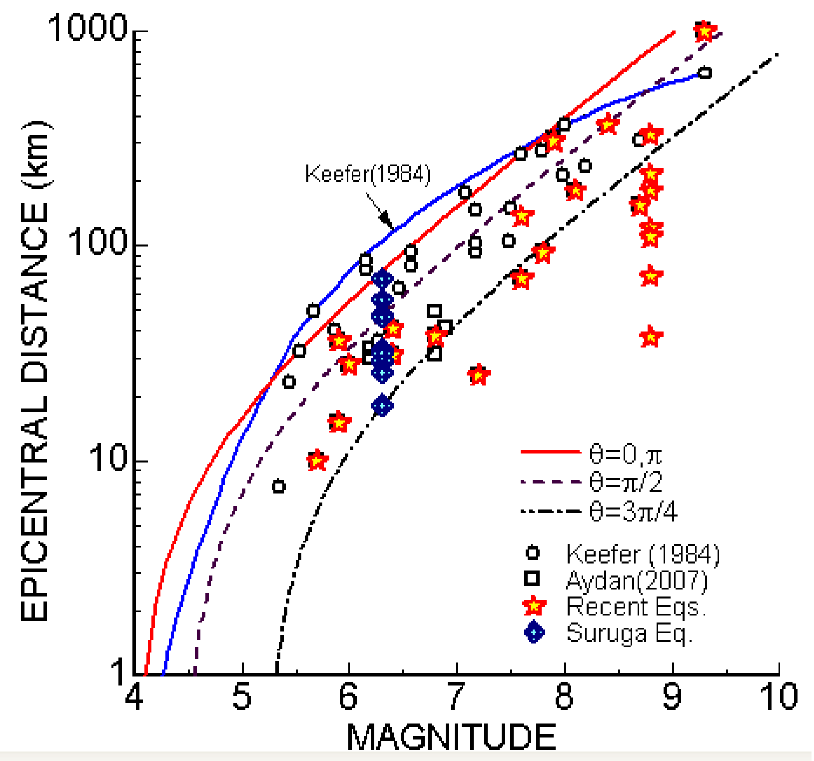
(i) Banjo waterfall

(j) West shore of Izu Peninsula between Heda and Toi

Figure 39: Example of some of slopes failures caused by the Suruga earthquake



(a) Coherent slopes



(b) Disrupted slopes

Figure 40: Comparison of empirical relations with observations on slope failures

9.4 Ground Liquefaction and Its Effect on Structures

It is well known that there are many case histories of ground liquefaction in Shizuoka prefecture in past earthquakes such as 1854 Ansei, 1891 Nobi-beya, 1935 Shizuoka and 1944 Tonankai earthquake (i.e. Wakamatsu 1991). As the magnitude of the earthquake is intermediate and duration is about 10 seconds, it is expected that the ground liquefaction would be limited. Nevertheless, the authors observed ground liquefaction in many locations as shown in Figures 41 and 42. Although no sand-boiling was observed in some of cases, the ground settlement in many locations (i.e. Shizuoka, Haibara, Sagara, Yoshida and Yaizu) was a clear indication of ground liquefaction. It was also interesting to observe the settlement of cemetery stones into the ground in liquefied areas.

The effects of ground liquefaction on structures are observed as settlement, uplift or lateral movement. The authors observed such effects on structures in areas of alluvial deposits, which are potentially liquefiable (Figure 43). The most severe effects of ground location was observed in Sagara fishing port, where quaywalls moved towards the sea, causing the separation cracks and settlement in the pavements. The maximum settlement and lateral movement of quaywalls were about 400 mm and 600 mm, respectively. The most severe movement was perpendicular to the fault strike. The top soil was sand (Figure 41(f)), which was observed by the authors when they visited the port on July 1, 2010 to see how the restoration was carried out. The most spectacular ground liquefactions were observed in Omaezaki West Wharf, Sagara-Sakai fishing port and Susuki area of Sagara. Although the filling material of the West Wharf contains mudstone and sandstone of Sagara formation, the ground liquefaction was wide spread and the diameter of sand volcanoes was about 5 m in some locations. The movement of water breaks and quay walls ranged between 25-40 cm in the West and Jitogata wharfs of Omaezaki port. The maximum ground velocity obtained from the acceleration record taken at the Omaezaki port by The Port Authority of Japan was about 40 cm/s.

The ground liquefaction caused the uplift of deep-sea water tank and rupturing connections pipes. The relative settlement between the non-treated ground and Aquas building caused streching of pipes of the facilities as well as the rupturing of concrete foundation of the stairs.

The grain-size distribution of soil samples, the estimation of lateral spreading and the limiting distances as a function of earthquake magnitude for ground liquefactions are shown in Figure 44, 45 and 46. As noted from these figures, the observations are in accordance with empirical relations.

(a) Yaizu New Fishing Port (b) Ibuchi (Yaizu)

(c) Yoshida Fishing Port (d) Joshin Temple – Haibara (e) Sagara-sakai

(f) Sagara fishing port (g) Susuki-Sagara

(h) Omaezaki west Wharf

Figure 41: Views of ground liquefaction at several locations

(a) Yaizu Deep-sea water plant storage tank

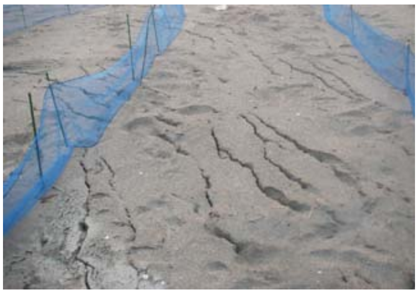
(b) New Yaizu Fishing Port

(c) Aquas building

(d) Sagara-Sakai Hirata port

(e) Sagara-Sakai

(f) Yaizu fishing port



(g) Susuki

Figure 42: Ground-liquefaction induced damage at several locations

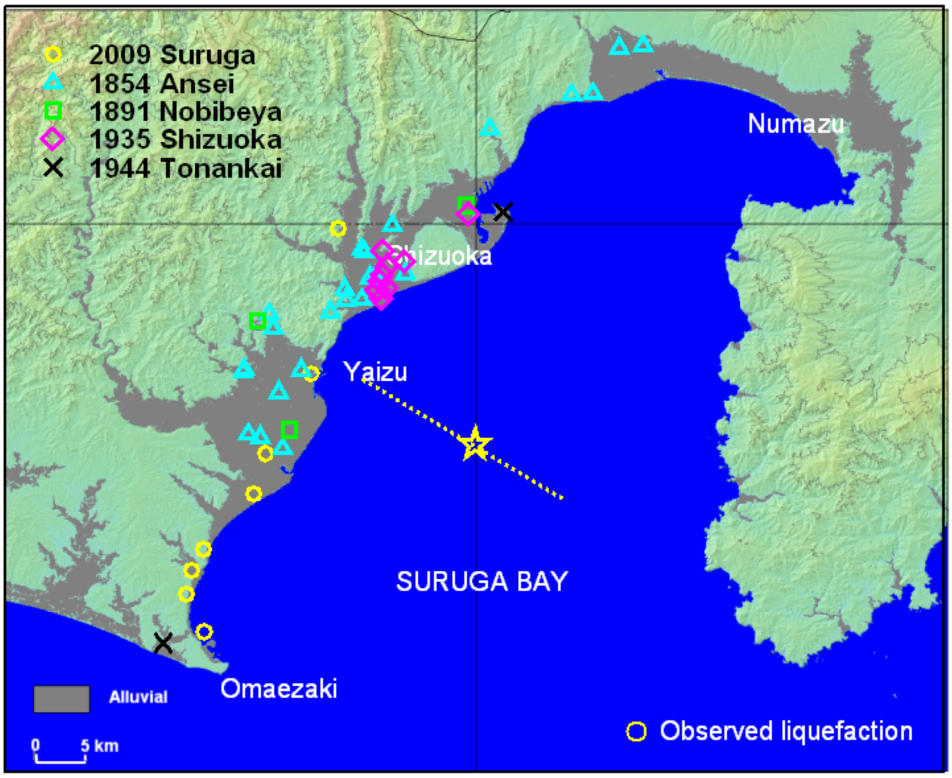


Figure 43: Comparison of observed liquefaction with those observed in past earthquakes

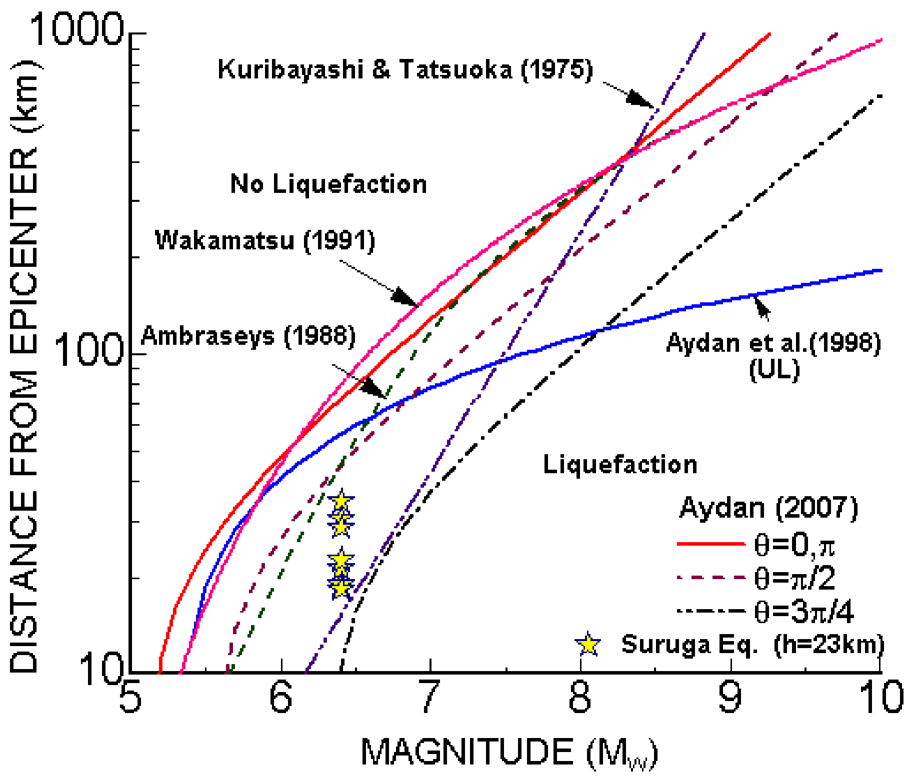


Figure 44: Comparison of various empirical relations between earthquake magnitude and distance of ground liquefaction with observations

10 TRANSPORTATION FACILITY DAMAGE

10.1 Roadways

The major damage to roadways was induced near the Makinohara Service area by the embankment failure (Figures 33 and 45(a)). This embankment failure disrupted the traffic on the TOMEI Expressway for about 5 days. The highway R59 was closed to traffic due to embankment and slope failures (Figure 45(b)). There was some reduction of traffic to a single lane on Route 17 (Figure 45(c)) at locations where slope failures or rockfalls occurred. As the Tomei expressway was closed to traffic, the traffic jam on Route 150 was an extremely severe problem. Some sections of the second Tomei Expressway, which is now under construction, was temporarily open to traffic. Furthermore, there were some settlements of embankments next to viaducts and railways at various locations.

(a) Tomei Expressway (b) R59 Highway (c) R17 Highway

Figure 45: Damage to expressways and roadways

10.2 RAILWAYS

The effect of the earthquake on railway lines was almost none. The railway lines are the JR Shinkansen line, JR Tokaido Local Railway line and the local Shizutetsu railway line between Shimizu and Shizuoka. Railways companies carried out necessary inspections on railways (Figure 46). The train services were temporarily halted.

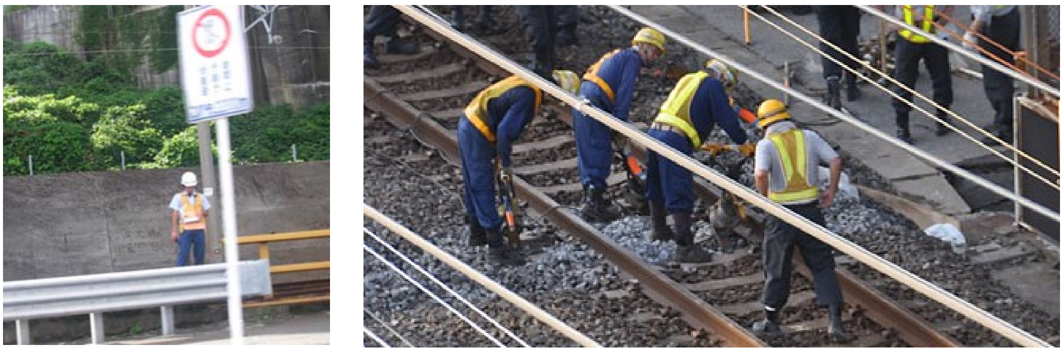


Figure 46: Inspection of railways and the restoration of disrupted parts

10.3 BRIDGES

There are four major rivers, namely, Fujikawa, Abe, Oikawa and Tenryu Rivers in Shizuoka Prefecture. There are almost no damage any of bridges crossing these major rivers. However, slight damages were observed at several bridges such as Sagara Bridge over Hagima River and Susuki River Bridge on R150 (Figure 47). The damage at Sagara Bridge was due to settlement of the embankment of at both sides of the bridge.

(a) Sagara bridge on R150 over Hagima River

(b) Susuki River bridge on R150

Figure 47: Views of damage to several bridges

10.4 PORTS

The major ports in the earthquake-affected areas are Shimizu Port, Ohkawa Port, Omaezaki Port, Yaizu Port and Numazu Port. There are also many smaller ports mainly for fishing ships. Settlement and lateral movement of quay-walls were observed almost in all ports around the west shore of Suruga Bay. The ground liquefaction as well as intense shaking by the earthquake heavily damaged the Sagara fishing port. All quay-walls moved towards the sea. Nevertheless, the movement of the quaywalls on the western side of the port moved more than 600mm in north-direction while the eastern quaywall moved more than 400mm towards south. The damage at Yaizu fishing port was in the form of settlement and lateral movement up to 250mm. The segments of the wave-break at Jitogata wharf displaced and separated up to 350 mm. Extensive ground liquefaction was observed in the west wharf of the Omaezaki port. The filling material of the reclaimed area of the wharf liquefied and caused lateral movements and settlement. It was also interesting to note that some tetra-pods were ruptured due to the earthquake, indicating very high ground accelerations.

Figure 48: Damage at Yaizu new fishing port

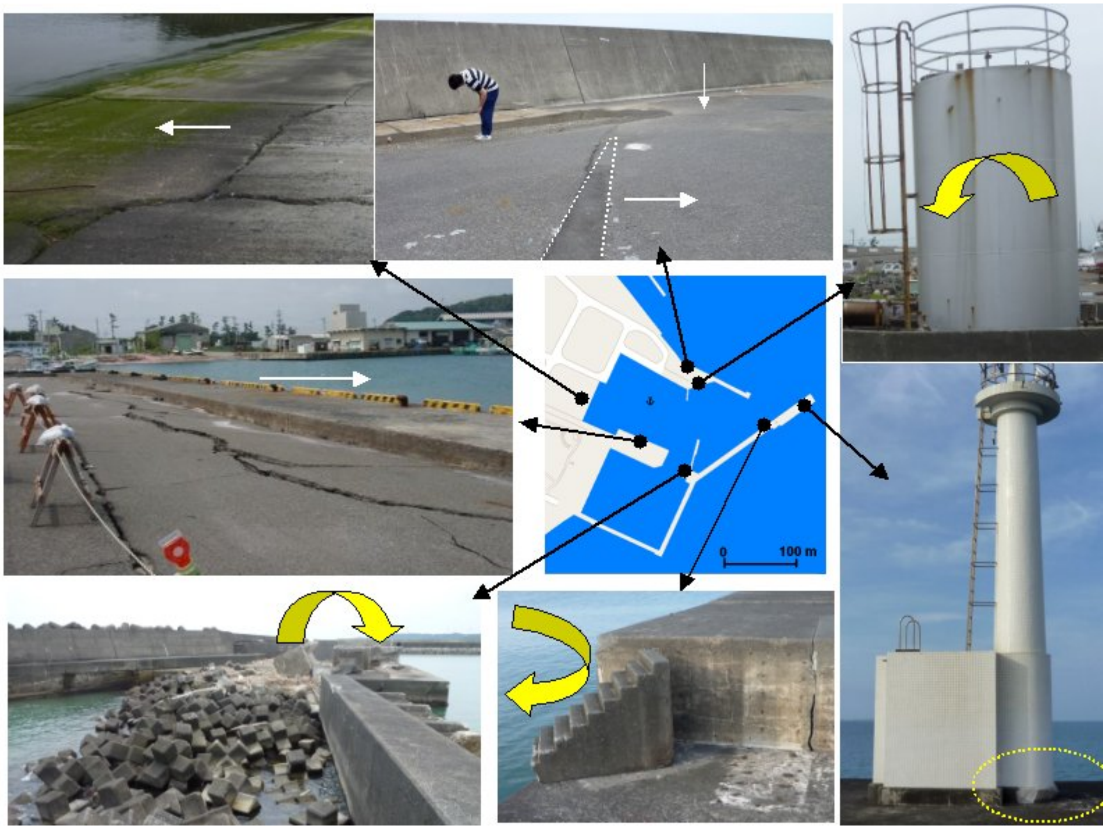


Figure 49: Damage at Sagara fishing port

Figure 50: Settlement, separation and lateral movement of concrete blocks of the wave-break of Jitogata fishing port

Figure 51: Damage at the west wharf of Omaezaki port on reclaimed land

10.5 Underground Structures and Rock-sheds

There are many roadway and railway tunnels in the earthquake-affected area. No major damage was reported for these underground structures even at portals, which are quite vulnerable to earthquakes. Figure 52 shows some examples of tunnels in Yui and Shizuoka, an underground passage next to the failed masonry retaining wall in near Sunpu Castle and underground observation gallery in Omaezaki. As noted from pictures of these structures, the earthquake caused no visible damage.

Figure 53 shows pictures of unsupported caverns excavated in andesite in Uchiura and Heda in Izu Peninsula. The caverns were probably excavated before the Second World War as rock shelters. These caverns are still used for storage of goods. Although almost all these caverns were structurally stable, there were some small fallen rock fragments due to ground shaking.

An interesting observation was done on a reinforced concrete rock-shed at Okuzure region. There were numerous fallen andesite rock blocks up to 1m in diameter at the base of rock-shed. These rock blocks were fallen down from the steep slopes and hit the rock-shed and frame-type shotcrete protection of the slope at various locations as seen in Figure 54. Although some parts of the rock-shed spalled due to the impact of rock blocks, the rock-shed was structurally safe and functional.

Figure 52: Non-damaged underground structures in the earthquake affected area

Figure 53: Views of underground caverns in Izu Peninsula

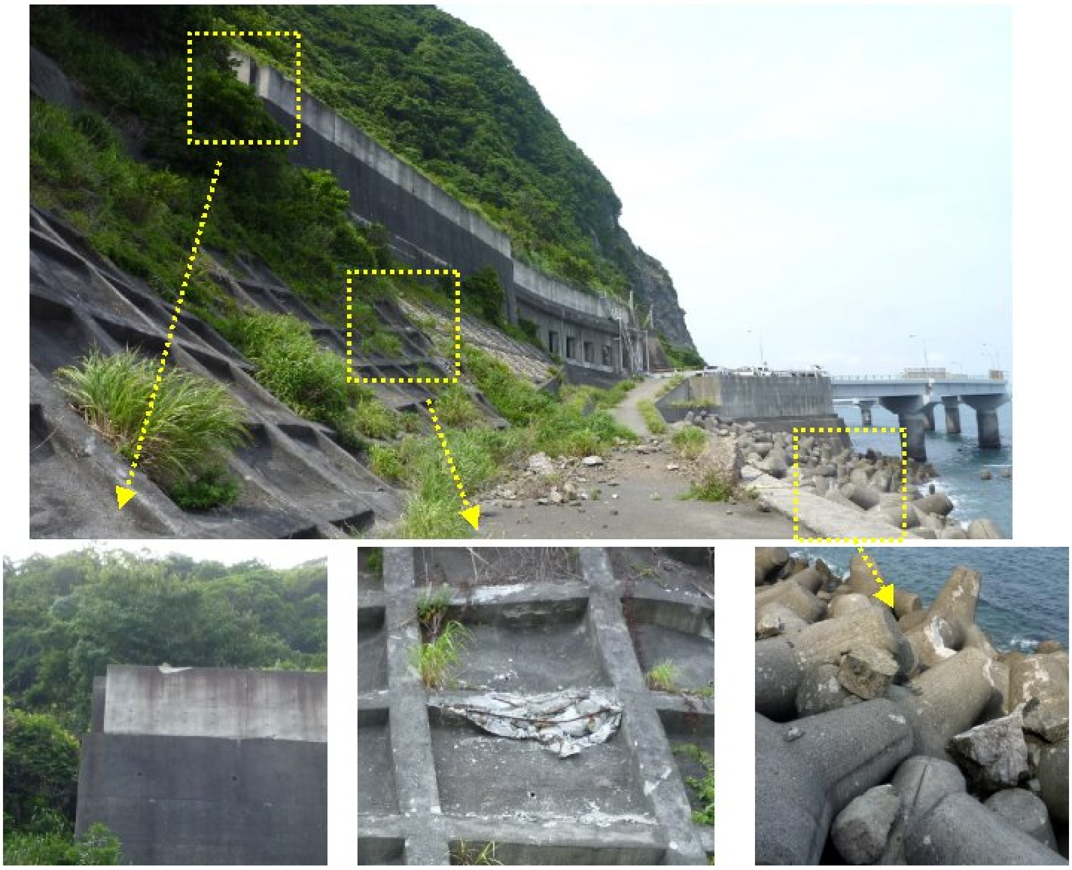


Figure 54: Slight damage to a rock-shed in Okuzure

11 INDUSTRIAL FACILITIES

11.1 Storage Facilities and Factories

There are many industrial facilities around Suruga Bay. Although small-scale damage due to rotation and dislocation due to ground shaking was observed, there was no major damage in any industrial facility. The silos at Shimizu port and Ohkawa port were all intact. There are also many oil and gas surface and semi-underground storage tank yards around Suruga Bay. No damage was reported in any such facilities. The authors investigated some of cylindrical and spherical storage tanks in the vicinity of Yaizu-Ohkawa port area (Figure 55). There was no visible damage to any of tanks in the area, although it is very close to the earthquake epicenter. A small oil-tank in Sagara fishing port was only tilted due to lateral movement of the ground.

There was some damage to beer containers at the Yaizu Sapporo Beer Factory. The damage was caused by the breakage of bottles of beer due to toppling of beer bottle containers as seen in Figure 30.

Figure 55: Non-damaged cylindrical and spherical oil and gas storage facilities

11.2 Deep-sea Water Suction Plant

Yaizu Deep–sea Water Suction Plant is one of the earliest facilities of its kind in Japan. There are two steel-wire armored polyethylene pipelines with a outer diameter of 270mm at depths of 397 m and 687 m. These pipelines are laid onto a canyon-like natural trench in the sea bottom of Suruga Bay without any anchorage as illustrated in Figure 56. The water tank of the deep-sea water suction plant was uplifted due to ground liquefaction and the pipes around the tank were ruptured (see a view of the tank in Figure 42). Following the earthquake, there was no variation on the quality of deep-sea water sucked at a depth of 397 m. However, the seawater of the pipeline sucking water at a depth of 687 m became muddy and its temperature was higher than that previously recorded. The authorities suspected that some damage to the pipeline might happen due to the earthquake.

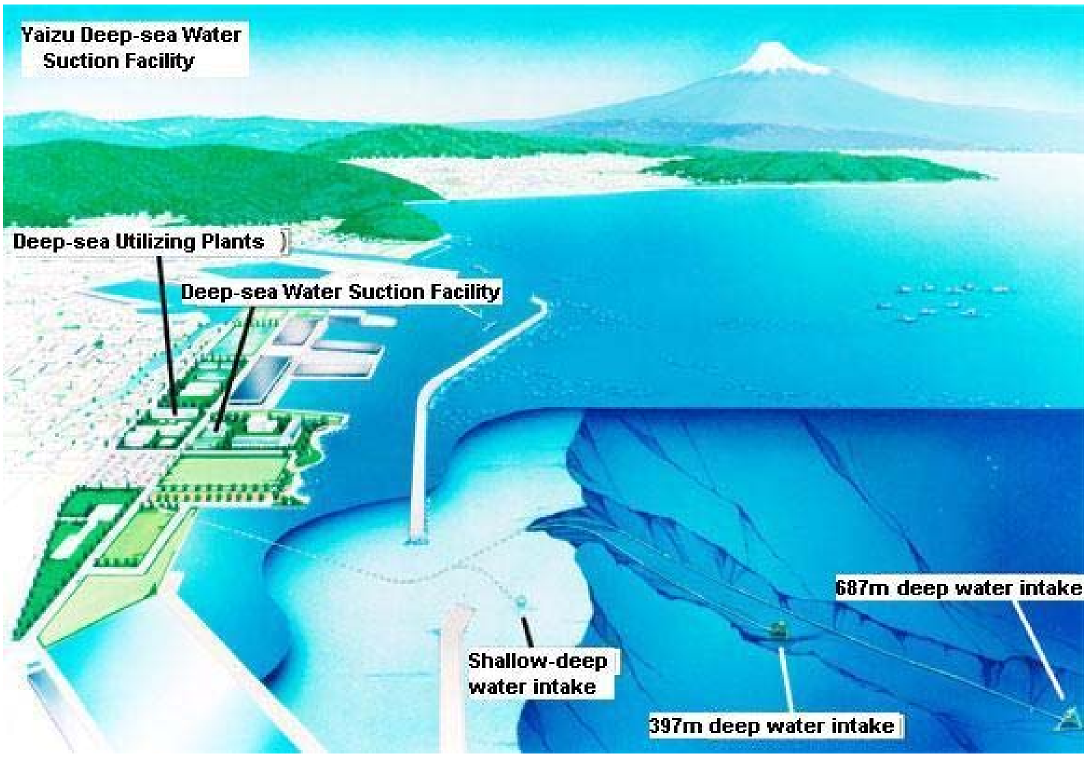


Figure 56: An illustration of Yaizu deep-sea water suction plant (from Shizuoka Prefecture)

The authorities asked Japan Marine Japan Agency for Marine-Earth Science and Technology (JAMSTEC) to investigate the condition of the 687 m pipeline. The JAMSTEC (2010) carried out the first investigation in December 2009. A remotely operated unmanned exploration (named as HYPER-DOPLHINE) was used for the visual inspection of the pipeline and its surrounding. The inspections by the HYPER-DOLPHINE indicated that the 687m pipeline was displaced by more than 2 km from its original position and the pipeline was thorn apart. In the vicinity of the ruptured pipeline, shipwrecks and muddy sediments were found (Figure 57).

The JAMSTEC undertook a Bathymetric surveying in the vicinity of the ruptured pipeline using a multi-beam echo-sounder in order to understand the cause of the pipeline rupture from February 27th to March 1st, 2010. The multi-beam bathymetric survey data was compared with those from 2004 and 2006 surveys. The results showed that the seafloor was subsided after the earthquake, about 5 km off the coast of Yaizu City (138°23’ E, 34°52’ N) at a water depth of 600 meters. The subsequent high-resolution underwater mapping revealed a horseshoe-shaped scarp. This is interpreted as a geologic evidence for a submarine landslide, which is 450 meters wide and 10 to 15 meters deep. Therefore, it was concluded that the submarine landslide caused the rupture of the pipeline.

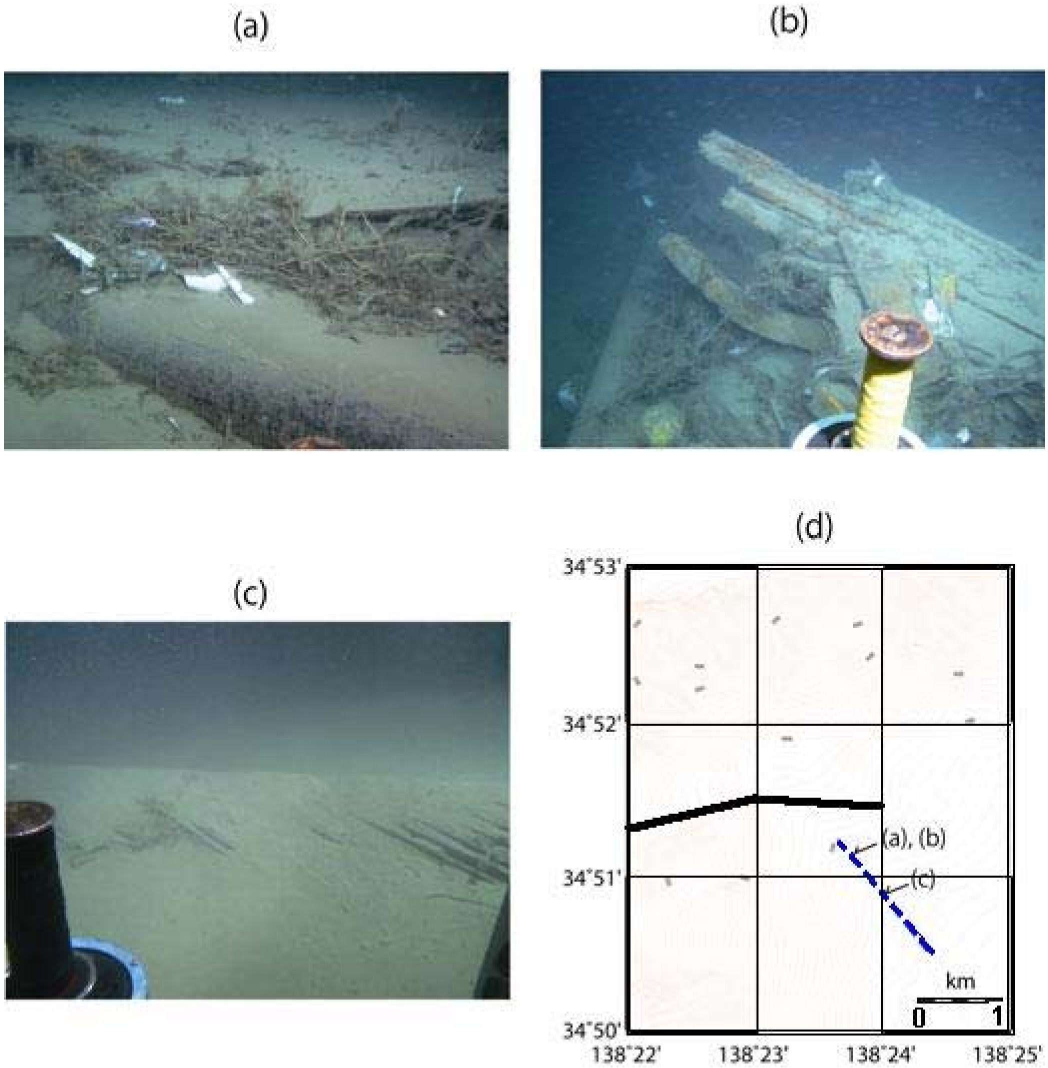


Figure 57: Views of the pipeline and its original position and location of the ruptured part (dotted line) (from JAMSTEC, 2010)

11.3 Hamaoka Nuclear Power Plant

The Hamaoka nuclear power plant owned by the Chubu Electric Power Company is about 43.6 kilometers away from the hypocenter (Figure 58). Two reactors (units 4 and 5) were in operation during the earthquake and they were automatically shutdown. The Reactor 3 was already shutdown for periodic inspection. Reactors 1 and 2 were permanently out of service for decommissioning. The reactors, units 4 and 5, are both boiling water reactors with the capacity of 1092 MW and 1325 MW, respectively (Figure 59).

Only minor damage to some masonry and fittings in the plant buildings has been found so far. The sloshing of water in a fuel-cooling pond at unit 5 occurred due to ground shaking to trigger a radiation alarm. This occurred inside the plant's sealed containment area and monitors in the building's exhaust stack recorded no release of radiation.

Chubu Electric Power Company (2009, 2010) reported that ground acceleration recorded at the plant was in the range of 100-160 gals for four of the reactors except Unit 5 reactor with a base acceleration of 426 gal (Figures 60 and 61). The ground amplification between –100m level and –2m level ranges between 2.1-3.5 times. The acceleration response spectra indicate that the structures having a natural period of 0.3-0.4s may be greatly affected by the earthquake. Although the distance was only 400 m from other reactors, the unusual high ground acceleration at Unit 5 reactor has received a great attention. Further investigations were undertaken for the cause of high ground acceleration at Unit 5 Reactor. The preliminary geological and geophysical explorations indicate that the accelerations may be amplified due to the existence of a low-velocity layer beneath the Unit 5 reactor.

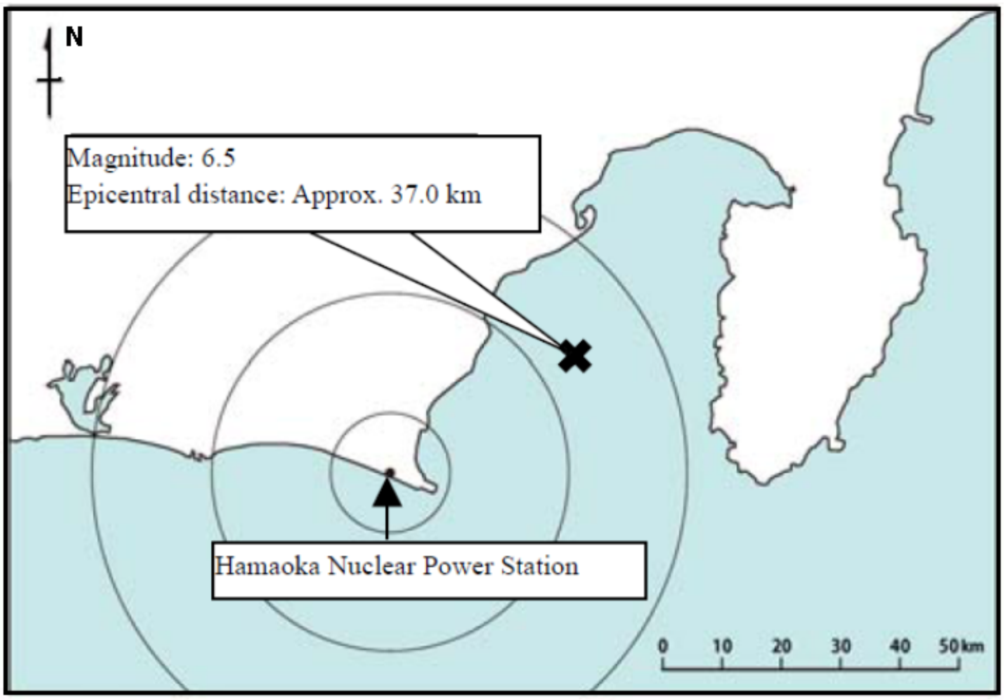


Figure 58: Location of Hamaoka Nuclear Power Plant and the earthquake epicenter (from Chubu Electric Power Company reports)

Figure 59: A satellite view of the Hamaoka Nuclear Power Plant and locations of Reactor Units

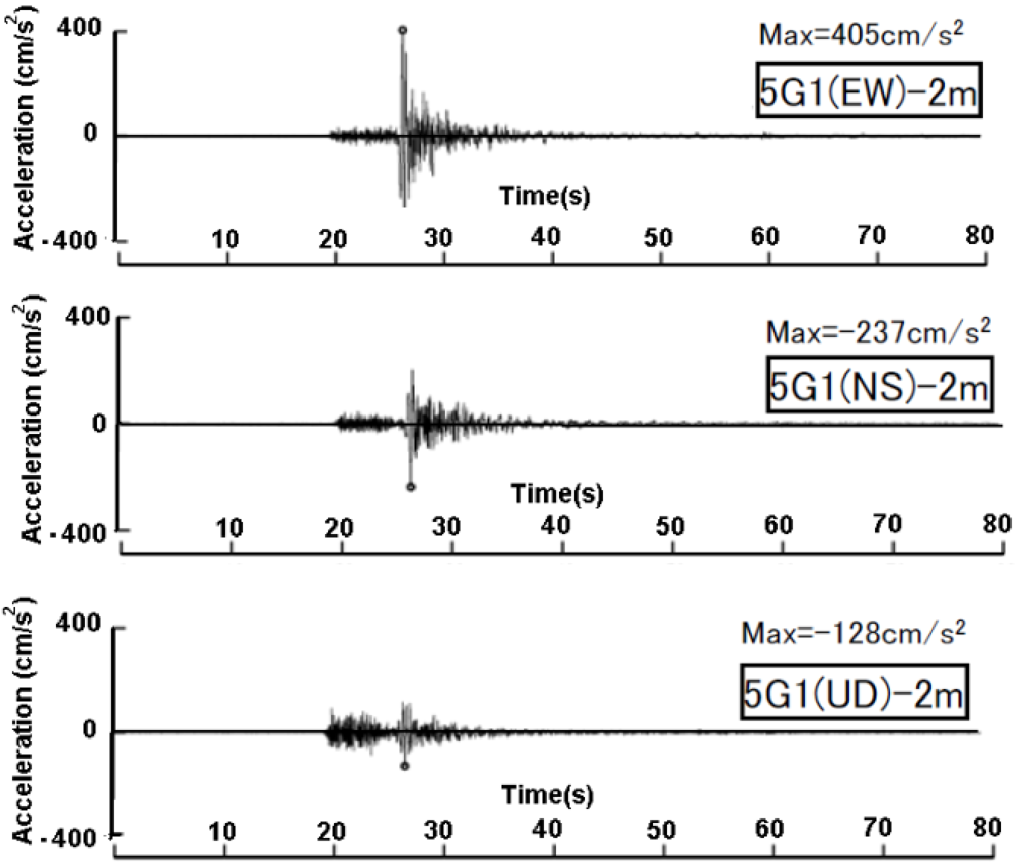


Figure 60: Acceleration records at Unit 5 Reactor at –2 m ground level (arranged from Chubu Electric Power Company reports)

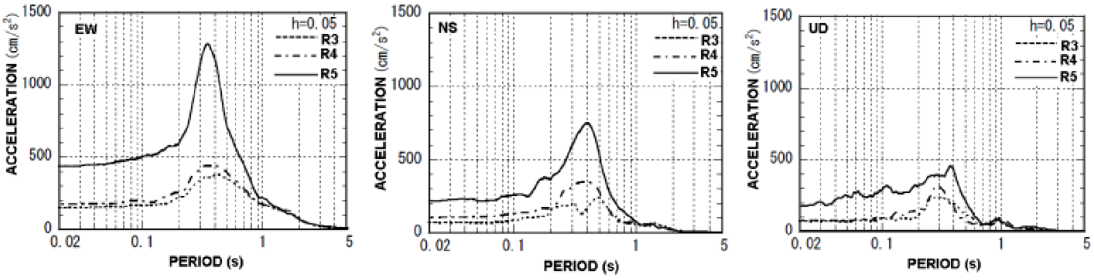


Figure 61: Response spectra of Reactor Units 3,4 and 5 at Basement 2 level (arranged from Chubu Electric Power Company reports)

12 LIFELINES

Chubu Electric Power Company reported that 9500 households were out of power in Aoi Ward and Shizuoka City as well as other parts of Shizuoka prefecture. The power was back on August 12, 2009. 9 utility poles were broken in Kawane town.

Damage to water distribution networks occurred in Shizuoka and Kanagawa prefectures. 57371 households in Shizuoka Prefecture and 2053 households in Kanagawa Prefecture were out water. The water could not be supplied to 28500 households in Makinohara and Kakegawa Cities. The water supply could not be achieved until August 13, 2010 in Makinohara City. Figure 62 shows some examples of damage to water pipes.

(a) Suruga ward of Shizuoka City (b) Makinohara City

Figure 62: Damage to water distribution pipes.

Tokai Gas reported that gas leakage occurred at 12 sites due to ruptured gas pipes. Figure 63 shows two examples of gas leakage in Shizuoka City.

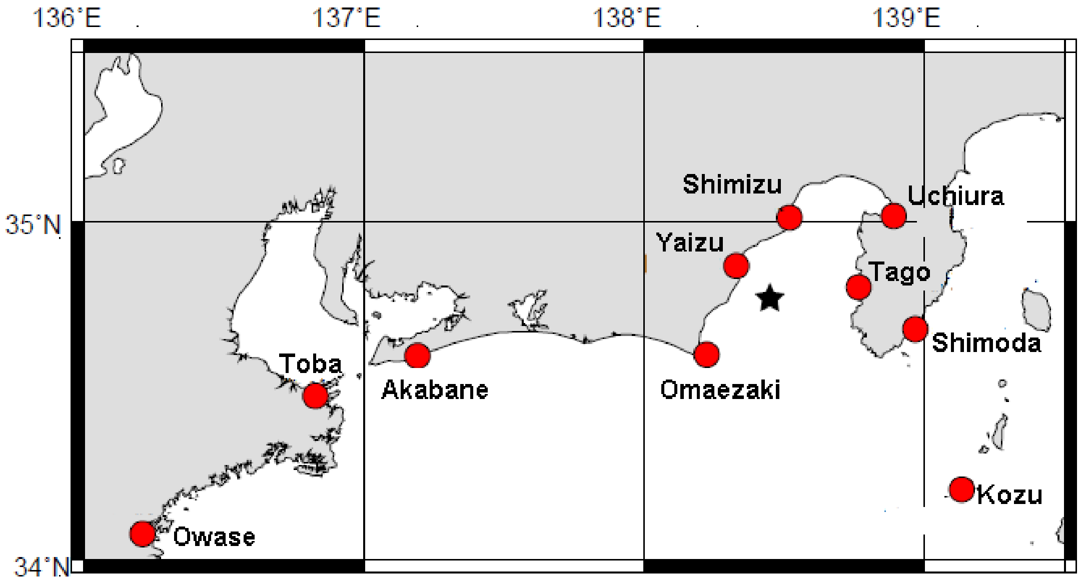
Figure 63: Views of gas-leakage sites in Shizuoka City (from newspapers)

13 TSUNAMI

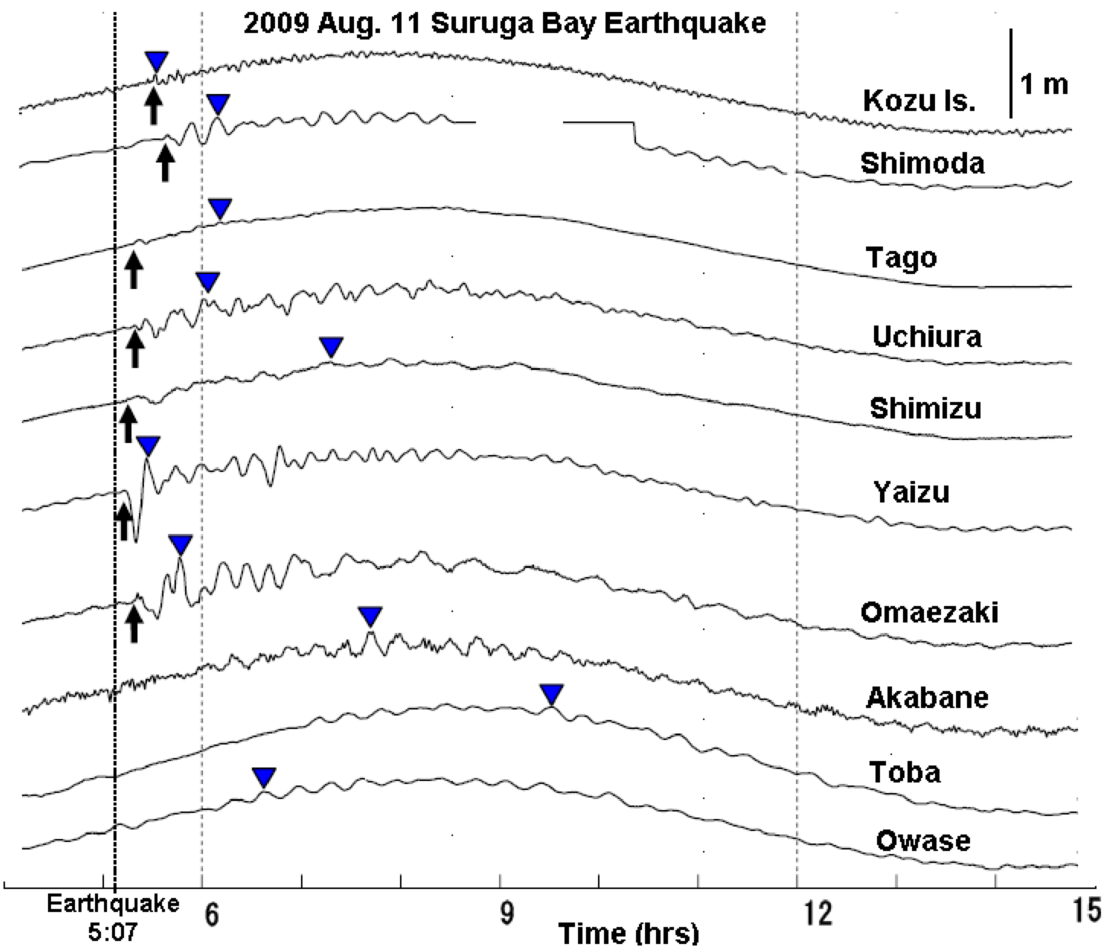
The earthquake caused a small tsunami around Suruga Bay and nearby areas (JMA, 2010). The nearest observation location is Yaizu port and tsunami wave of receding type was observed 5 minutes after the earthquake occurrence and the amplitude was about 62 cm. The second wave arrival was 12 minutes after the first wave and its amplitude was 36 cm. Figure 64 shows the records of tidal waves at various ports and Table 2 summarizes the arrival time and amplitude of tsunami waves. As the tsunami wave height was very small, there was no damage.

Table 2: Characteristics of tsunami waves

Location	First tsunami wave				Maximum tsunami wave	
	Arrival Time	Height (cm)	Sense	Arrival Time lag (minutes)	Arrival Time	Height(cm)
Yaizu	5:12	62	Down	5	5:24	32
Shimizu	5:14	2	Up	7	7:17	6
Tago	5:17	3	Up	10	6:08	4
Uchiura	5:18	2	Up	11	6:01	17
Omaezaki	5:20	5	Up	13	5:47	36
Kozu Is.	5:28	9	Up	22	5:29	9
Shimoda	5:34	4	Up	27	6:05	13
Akabane					7:41	16
Toba					9:32	7
Owase					6:37	6



(a) Locations of tsunami monitoring stations



(b) Records of tidal waves

Figure 64: Locations of tsunami monitoring stations and tidal wave records

14 EARTHQUAKE EARLY WARNING SYSTEM (EEWS)

Japan Meteorological Agency introduced a new system of early warning system for earthquakes. Figure 65 shows the warning time around the epicenter issued for the 2009 Suruga Bay earthquake. The system was successful for issuing warnings for the given specified conditions. Nevertheless, this system was of no use for people in the close vicinity of the earthquake epicenter, who were waken up by the intense ground shaking and falling objects. Although the system may be usefull for stopping the operation of large industrial plants, power plants and trains and roadway traffic in areas with a warning time period of more than 10s, it is practically useless for people, who were directly hit by the earthquake.

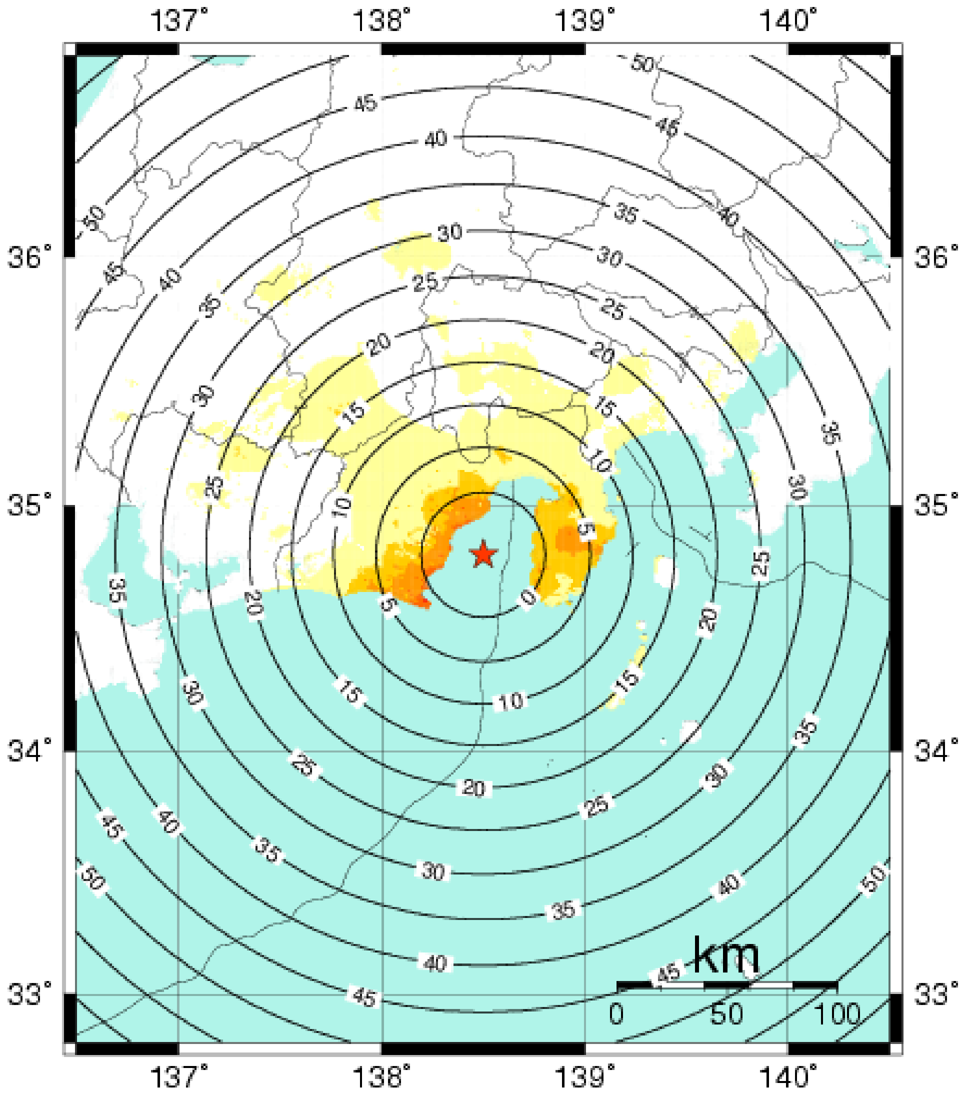


Figure 65: Warning time contours around the earthquake epicenter

14 CONCLUSIONS AND LESSONS

The 2009 Suruga Bay earthquake had an intermediate magnitude and the damage caused was very light in spite of high ground acceleration exceeding 0.7g. The reason for light damage may be the preparedness of the Shizuoka Prefecture against earthquakes, where M8 class Tokai earthquake is anticipated. However, this earthquake should be taken as a valuable lesson to check the issues associated with the earthquake preparedness of the Shizuoka prefecture against the anticipated Tokai earthquake. The conclusions and lessons from this earthquake are as follow:

1) The retrofitting of existing buildings and of various engineering structures was quite effective for reducing the disasterous effect of the earthquake.
2) Widespread ground liquefaction was observed although its effects on structures were quite small in this earthquake. However, this earthquake clearly showed that the areas over alluvial deposits are quite vulnerable to ground liquefaction, which may have great implications on assessing the effect of ground liquefaction in the case of the anticipated Tokai earthquake.
3) The failure of high embankment of TOMEI expressway clearly showed the vulnerability of this expressway against earthquakes. Therefore, countermeasures against embankment failures with the consideration of shaking characteristics of the anticipated Tokai earthquake are urgently necessary.
4) Many natural rock slopes failed and most of the failures occurred in anticipated regions. Although the scale and extent of slope failures caused the 2009 Suruga Bay earthquake did not affect residential areas and roadways, such failures may have tremendous effects in case of the anticipated Tokai earthquake. Therefore, the slope failure risk must be based on the structural geological features of particularly natural rock slopes.
5) The closure of TOMEI Expressway due to the embankment failure clearly indicated the importance and necessity of alternative routes. Four large rivers, namely, Fujikawa, Abe, Oi and Tenryu, flow through the Shizuoka prefecture. As the number of bridges over these bridges is not many, they caused very long traffic queues and traffic jams. Although the second TOMEI Expressway would serve as an alternative route, the construction of more bridges are necessary at the Shizuoka Prefecture is the most important route connecting East and West Japan.
6) The fall of accessory roof panels and other fixtures in large halls and sport facilities indicated their vulnerability to earthquakes. Therefore, urgent countermeasures must

be implemented in order to prevent or restrict the fall of such accessories in large halls and sport facilities.

7) Tsunami warning and the closure of automated tsunami gates were effective. Nevertheless, some measures for the quick closure of non-automated tsunami gates are necessary. Further considerations on the closure of tsunami gates in case of power loss must be taken into account.
8) Early earthquake warning system was successfully operated. Although this system could be usefull for regions having the early warning period of more than 10s and for stopping or halting the operations of important with long natural periods and roadways and railways, it is not of great help to regions in the close vicinity of the earthquake epicenter as in the Suruga Bay earthquake. In other words, this system would not be of any use for people living around Suruga Bay where the Tokai earthquake is anticipated.

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