HAZARDS OF ACTIVE FAULTS AND PROPRIETY OF LAND-USE CONTROL ON FAULT TRACES

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Abstract In Japan, many people have believed that the areas along active faults are the most dangerous places when fault movement recurs. They have been anxious about the collapse caused by fault displacement of buildings standing on fault traces. Although movement of an active fault beneath the Kobe and Awajishima region indirectly caused the destructive seismic disaster of the 1995 Hyogo-ken Nanbu Earthquake, no clear relationship was found between the concentration of damages and the traces of surface fault break. This fact indicates that the real hazards of fault movement are not restricted to within the narrow zone along the fault trace. There are two reasons why active faults are dangerous to people in Japan. One is that an active fault will cause severe seismic disaster through the occurrence of a large earthquake with shallow focus. The other is that fault movement will cause the functional breakdown of the national lifelines. When these lifelines are broken and suspended for a long period, social and economic confusion will occur not only in Japan but also on an international scale. Therefore, the government should reconsider and reinforce useful measures against active faults in Japan. The author proposes here how the hazards and land-use control along the active faults should be managed reasonably and realistically based on information concerning the severe damage caused by the Hyogo-ken Nanbu Earthquake.

Key words: Hyogo-ken Nanbu Earthquake, land-use control, active fault, fault trace, disaster zone

1. Introduction

In the early morning of January 17, 1995, a destructive earthquake of magnitude 7.2 on the Richter scale abruptly hit the Hanshin (Kobe-Osaka) and Awajishima Island region including the densely populated area of Kobe City, southwestern Japan. This onshore shallow earthquake, named the 1995 Hyogo-ken Nanbu Earthquake (the Great Hanshin Earthquake), caused severe unprecedented disaster including over 5,500 fatalities and over 200,000 burnt and collapsed houses in the Hanshin and Awajishima region.

The earthquake was generated by the movement of a set of active faults, which lie from the northwestern part of Awaji Island to the southern foot of the Rokko Mountains west of Kobe. Therefore, the word "active fault," which had been a technical term used only by a few scientists involved with the Quaternary geology and in referring to the geological hazard before the event, came to attract strong concern among people as an indication of the source of future destructive earthquakes.

From the viewpoint of the land-use administration in Japan, the social effects of the existence of active faults have never been discussed seriously except in relation to the site location of nuclear power plants. However, the precious lesson of the Hanshin Disaster will urge the central and local governments to reconsider and to reinforce measures for disaster prevention. In this trend of policy, some problems such as social and technological management of active faults and land-use control on and around the trace of active faults will become the major issues.

Therefore, the author proposes here how hazards and land-use control along the active faults should be managed reasonably and realistically based on information concerning the severe damage caused by the Hyogo-ken Nanbu Earthquake.

2. The Hyogo-ken Nanbu Earthquake and Active Faults

Dispute on the origin of the severely damaged zone in Kobe

Although the magnitude of the Hyogo-ken Nanbu Earthquake was no larger than others which occurred on the Japanese Islands in these several decades, the shallow earthquake near the megalopolis caused different types of damage than that which resulted from a series of recent large shocks. The following are notable features of the structural damage in Kobe: the complete collapse of a large number of wooden houses, the collapse of ferroconcrete buildings with less than ten stories, the collapsed and sidelong overturned bridges of highways, and the liquefaction and consequent subsidence caused by the ground compacting in the reclaimed land along the coastal area.

The most conspicuous feature of the earthquake damage in Kobe was the occurrence of a long, narrow zone where the destruction of wooden houses and buildings was highly concentrated. The zone with 1 to 2 km width between Route 43 (south) and the Hankyu Kobe Line (north) continually ran for a 25 km distance from Suma Kaigan to Nishinomiya City. At the proximal part of the zone, 70 to 80 % of the wooden houses were destroyed by the strong ground motion. The distal part of the zone also showed the collapse of more than 30 % of all wooden houses (Koketsu, 1995a, 1995b). The number of fatalities was also concentrated in this zone, with 90 % of the deaths resulting from the victims being crushed.

The detailed survey by the Japan Architecture Society also revealed the concentration of damaged buildings to be within a narrow zone on the south side of of the JR Tokaido Line. In the zone of 200 to 300 m width, over half of the ferroconcrete and steel framed buildings were destroyed. Shimamoto (1995) refers to this damage concentrated zone as the earthquake disaster zone (Fig. 1).

The origin of the earthquake disaster zone is now in dispute. The collapse of wooden houses by strong ground motion is generally correlated to the surface ground condition of the seismic area. Large earthquakes in this century including the 1923 Kanto Earthquake often showed the conspicuous concentration of damaged houses to be within

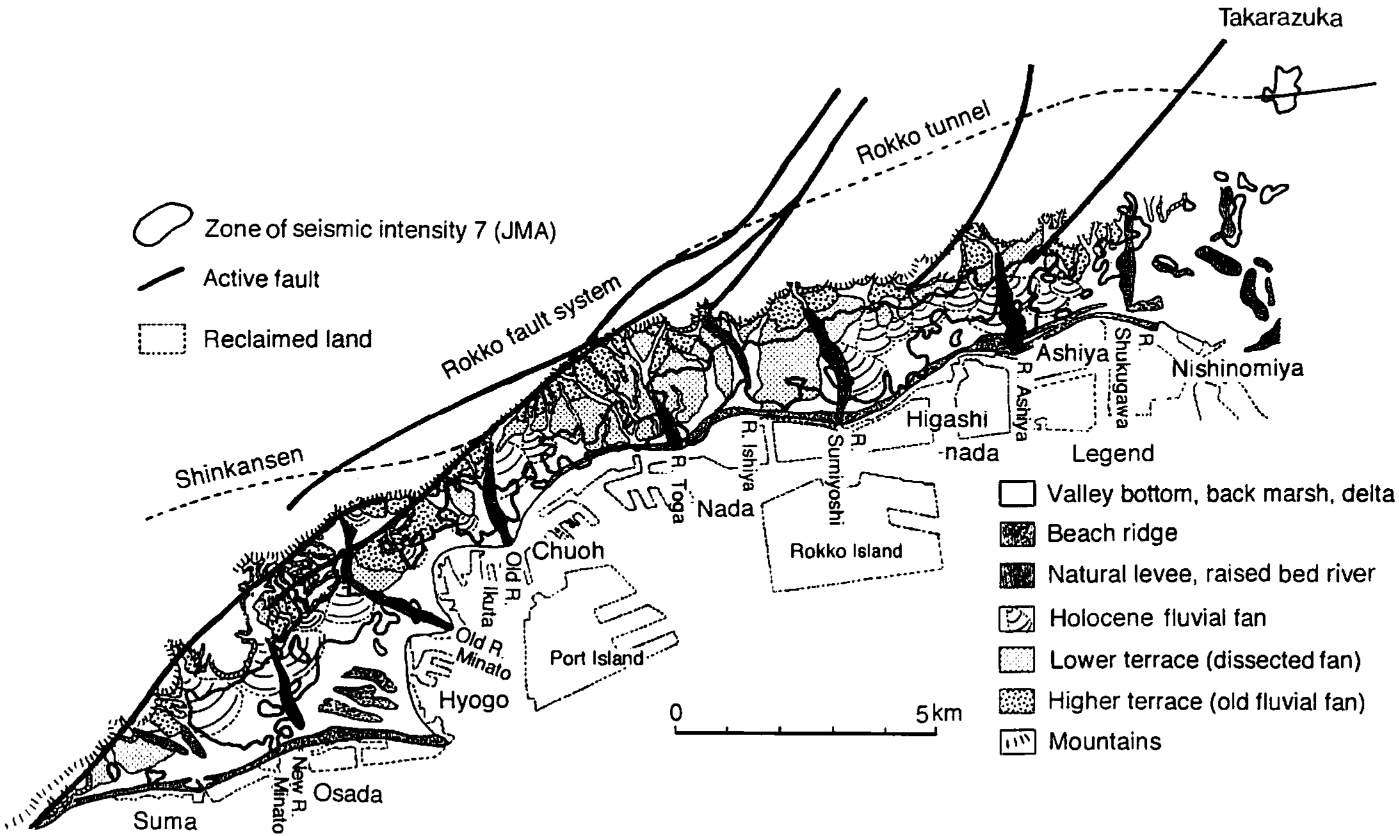

Fig. 1 Geomorphological map of Hanshin (between Kobe and Osaka) coastal plain and distribution of the earthquake disaster zone (modified Yoshioka, *et al.*, 1995, Ishikawa, 1995)

the soft ground area. However, the earthquake disaster zone in the Hanshin region did not correspond to the distribution of soft ground.

The populated area of Kobe City spreads on a long, narrow coastal plain with a 2 to 3 km width that is formed between the Rokko Mountains and Osaka Bay. This coastal plain consists of geomorphologic units that extend parallel to the Rokko Mountains. The geomorphologic units constituting the plain are hills along the southern foot of the Rokko Mts., middle and lower terraces of fluvial origin, composite fluvial fans, a deltaic lowland spreading on the south of Route 43, and reclaimed land along Osaka Bay (Huzita and Kasama, 1983; Ikeda, H., 1995; Yoshioka *et al.*, 1995). The disaster zone is not present in the deltaic lowland or in the reclaimed land areas with soft ground conditions but does correspond to the geomorphic boundary between the upland of composite fluvial fans and the deltaic lowland (see Fig. 1).

As for the origin of the earthquake disaster zone in Kobe, several interpretations have been proposed and discussed. One idea is that the movement of concealed active faults beneath the zone caused the severe damage on the surface. Shimamoto (1995) and Ikeda, Y. (1995) support this idea based on the observation of surface damage and the analysis of the emitting direction of seismic first motion resulting from the rotation of grave stones.

The other idea is that the concentration of damage into a long and narrow zone is due to the underground structure beneath the coastal plain of Kobe. The distribution of aftershocks, which indicates the fault plane of the deep-seated seismogenic fault and corresponds to the fault traces along the southeastern foot of the Rokko Mountains far from the earthquake disaster zone, supports this idea. One possible explanation for the origin of the narrow damaged zone is the occurrence of extraordinary ground-shakings along the edge of the deltaic alluvial plain. This phenomenon called "waterside effect" was firstly recognized during the 1994 Northridge Earthquake in California. The emission of strong ground motion at the edge of the plain is believed to be an effect of amplified seismic waves in the shallow and thin soft ground (Koketsu, 1995b).

Takahashi (1995) and Yoshioka *et al.* (1995) pointed out that the earthquake disaster zone corresponded to the area of relatively bad ground-condition where back marshes and swamps between cones of alluvial fans were located before the urbanization of Kobe. Midorikawa (1995) also pointed out that some natural and social conditions that were vulnerable to earthquakes had overlapped on the earthquake disaster zone. For example, the zone corresponds with the geomorphologic boundary between the upland and the alluvial lowland where it is believed that the ground motion intensifies. Moreover, old wooden houses with heavy roofs built before the amendment of the building code in 1971 have been concentrated in this zone.

We do not conclude which ideas are correct. Therefore, we need a more detailed survey of Awajishima, where fault break appeared on the surface, to obtain the relationship between the earthquake faults and the seismic damage to the buildings and wooden houses.

Earthquake fault and seismic damage

The second feature of the Hyogo-ken Nanbu Earthquake is the occurrence of an earthquake fault in the northern part of Awajishima Island. The earthquake fault means the surface fault rupture that occurs on the ground simultaneous with the earthquake, and includes several types of faults in tectonic origin. Ground ruptures due to the gravity process such as crown scarps and marginal cracks of landslides are excluded from the category of earthquake faults.

The surface fault ruptures appeared linearly along the northwestern coast of Awajishima Island, and extended for 10 km from Toshima Town to Ezaki lighthouse (Awata *et al.*, 1995). The earthquake fault having 1.7 m of right lateral slip and 1.3 m of vertical slip components (east side upthrow) in maximum indicates the recurrent movement of the Nojima fault, which has been recognized as an active fault by Mizuno *et al.* (1990). Many geological and seismological features suggest that the earthquake fault in Awajishima is a direct expression of the deep-seated seismogenic fault which generated the Hyogo-ken Nanbu Earthquake (Kikuchi, 1995; Hashimoto, 1995). Although the earthquake fault seems to extend into the Akashi Strait between Awajishima and Honshu, no surface fault appeared in the coastal region of Honshu, which is opposite to Awajishima.

The steep slope of the southeastern border of the Rokko Mountains has resulted from the cumulative movement of active faults since the middle Pleistocene. These faults, called the Rokko fault system, have shaped the conspicuous geomorphic boundary between the mountains and the coastal plain of Kobe.

No evidence of the surface fault break was found along the Rokko fault system in

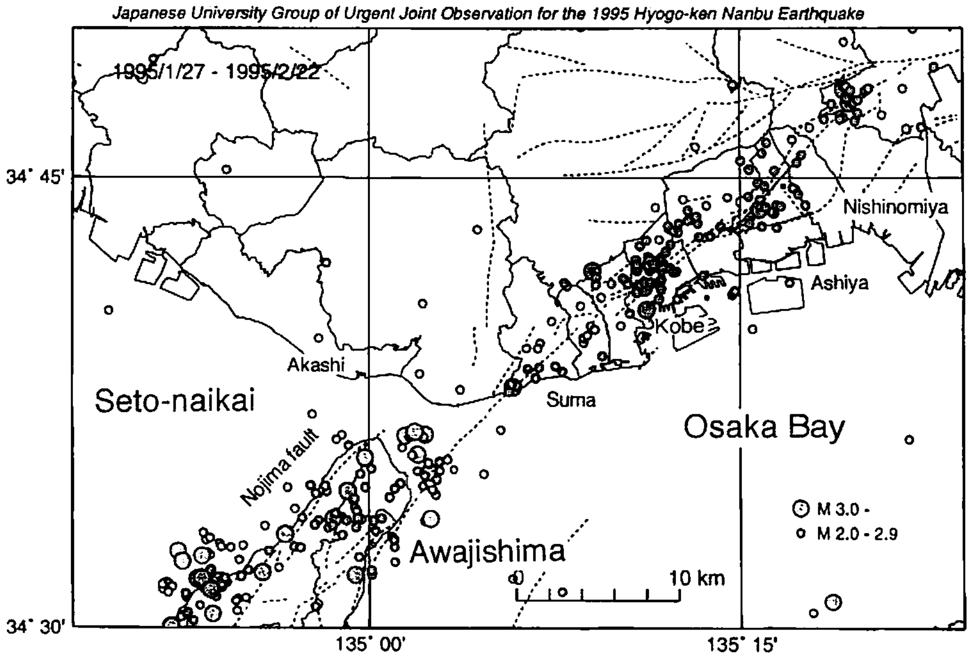

Fig. 2 Distribution of aftershocks of the 1995 Hyogo-ken Nanbu Earthquake observed from Jan. 27 through Feb. 22 (after Hirata, 1995)

spite of the detailed surveys completed since after the earthquake. However, the distribution of aftershocks since January 17 has corresponded to the trace of the Rokko fault system. The aftershocks have linearly arranged from Awajishima to Takarazuka for over 50 km (Fig. 2). This fact indicates that the deep-seated part of the Rokko fault system moved as a part of the seismogenic fault and caused severe shaking of the Hyogo-ken Nanbu Earthquake. Nevertheless, the fault break did not reach the surface of the ground in the Rokko-Kobe region.

Although some researchers hastily reported the occurrence of fault breaks in the coastal plain of Kobe, many geological surveys carried out afterward confirmed that such breaks were only surface cracks caused by the gravity process on the ground during the earthquake (Yoshioka *et al.*, 1995).

The distribution of the seismic damage in the Awajishima region shows the following two features: many collapsed houses and fatalities were concentrated in the alluvial plains along the coast where old wooden houses stood close together (Fig. 3); the degree of damage did not increase toward the trace of the Nojima fault. Of course, some houses that were located just on or near the fault trace were torn and wrecked by the fault displacement. However, some houses escaped collapse despite the fact that the fault had displaced the foundations of these houses. The seismic damage in Awajishima caused by the Hyogo-ken Nanbu Earthquake may have resulted from the soft ground condition and the lack of earthquake-proof-strength buildings.

These features did not show any direct relationship between the fault movement and the distribution of severe seismic damages in Awajishima. Accordingly, the author cannot approve the idea that the origin of the earthquake disaster zone in Kobe is attributed to the movement of a concealed active fault beneath the coastal plain.

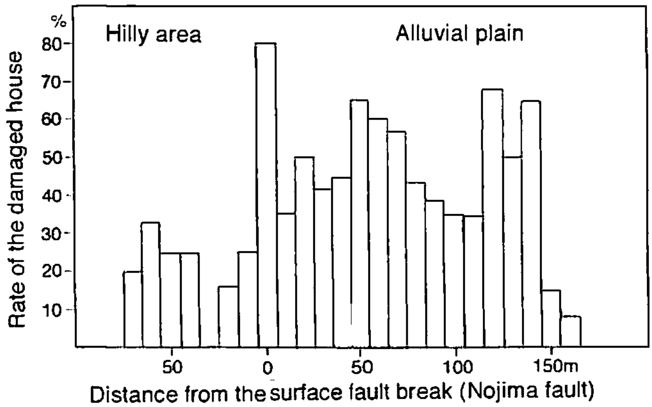

Fig. 3 Relationship between rate of damaged houses and distance from the surface fault rupture in Toshima, northwestern Awajishima (after Minagawa *et al.*, 1995)

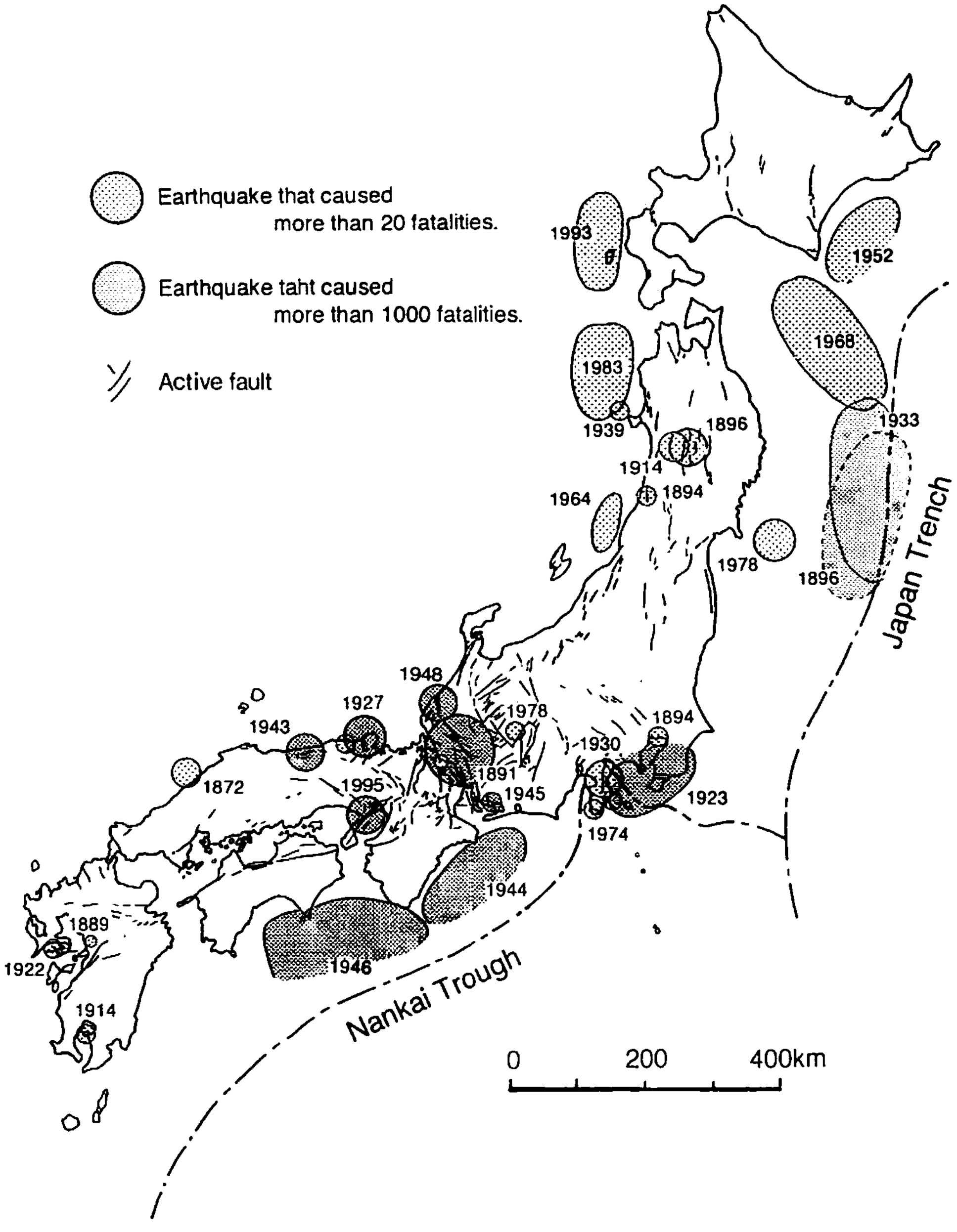

Fig. 4 Distribution of the earthquake and tsunami sources which caused the deaths of more than twenty people and more than 1000 people since the 1870 (data derived from Usami, 1987)
Each earthquake is shown by the tsunami source area in offshore and by the size of source dimension indicated by fault movement in onshore region. Therefore the size of the each circle does not always relate to the magnitude of earthquake. Numerals in or by the source area indicate the year of earthquake occurrence.

3. What is the Hazard on an Active Fault ?

The result of seismic damage in Kobe and Awajishima Island suggests the following two important issues. One is that the movement of an active fault caused the large earthquake with strong intensity resulting in severe damage. The other is that a negative relationship was found between the active fault and severe regional damage such as that which occurred in the earthquake disaster zone in Kobe. Therefore, if we consider the hazard associated with an active fault, it is better to separate the problem into the following two aspects: hazard from the seismogenic fault of which movement would cause the strong shaking: restricted hazard along the fault trace.

Seismic hazard of a shallow earthquake by an active fault

Figure 4 shows the earthquake and tsunami sources in and around Japan since 1870. The events causing deaths numbering over twenty were picked up in the figure. Seventeen of these cases were caused by onshore earthquakes with shallow focus. People in Japan usually imagine that severe seismic hazard is caused by huge earthquakes of the offshore trench-subduction type. However, the fact is that the onshore shallow earthquakes generated by active faults have caused half of the earthquake hazard in Japan since 1870. Moreover, the ten destructive earthquake disasters of which fatalities were over 1,000 have occurred in this same period. Six of them have been caused by shallow earthquakes associated with the movement of onshore active faults beneath the disaster region. These facts indicate that the onshore shallow earthquakes have caused disaster in Japan as frequently as the offshore huge earthquakes in the last century.

In general, the recurrence interval of earthquakes from an onshore active fault (more than 1,000 years) is longer than that of the offshore huge earthquakes from one segment of the subduction zone (about 150 years). The following are two possible reasons why the occurrence of onshore shallow earthquakes have equal frequency to that of the huge offshore earthquakes with relatively short intervals.

One reason is that there are many active faults in the onshore region of Japan. The infrequent movements of the many numbers of active faults show the frequent disaster on the whole of Japan. Another reason is that a shallow earthquake is apt to cause destructive damage because its seismogenic fault lies close to populated areas. These facts suggest that the active fault is dangerous in that it could cause a destructive earthquake.

The misunderstanding on the hazard caused by an active fault

Many people have believed that the most dangerous place for an active fault is on the trace line of the fault. This is correct for active faults from a macroscopic viewpoint. However, the microscopic observation does not always show the same tendency as the macroscopic. Concerning the damage distribution of the Hanshin Earthquake from macroscopic observation, the intensity of ground motion gradually decreased with the increasing of distance from the seismogenic fault as shown by Fig. 5. On the other hand, the microscopic damage observation for the 1974 Izu-Hanto-Oki Earthquake showed a little different conclusion. A NW trending earthquake fault called the Irozaki fault with

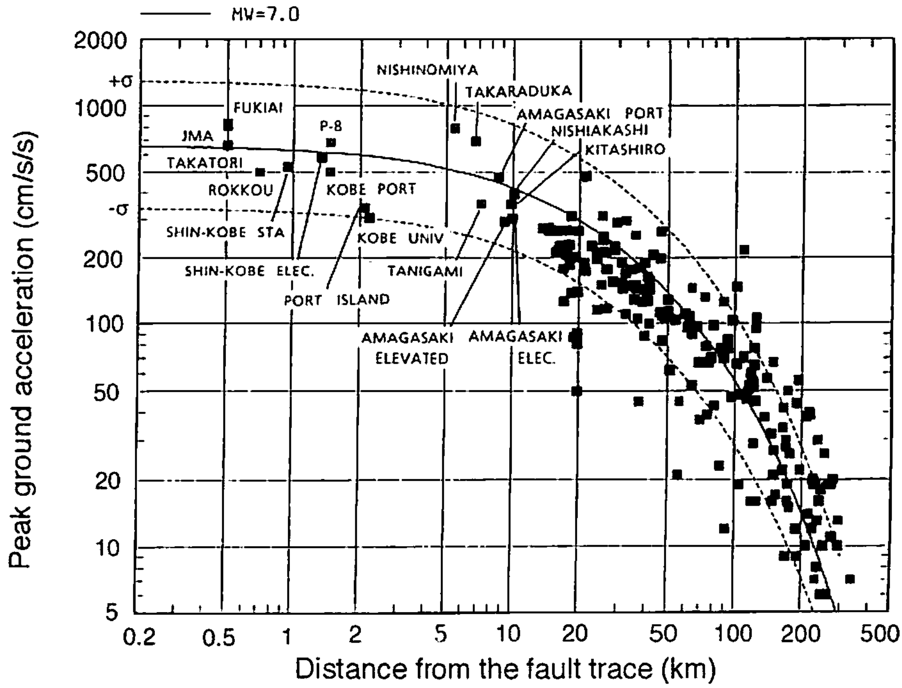

Fig. 5 Relationship between the observed peak acceleration and the distance of observation points from the active fault
Solid and broken curves show the standard values at Mw 7.0 earthquake computed from the formula of attenuation with distance and the ranges of standard deviation, respectively (Irikura, 1995).

a 6-km length occurred at the southern tip of Izu Peninsula during the earthquake, and caused some damage to the buildings standing on the fault trace. According to the detailed survey by Mochizuki *et al.* (1976), the damage produced a large regional differences among villages due to the conditions of the ground on which the villages were located.

In Irozaki where the fault conspicuously penetrated the valley bottom with thin sediment, the only houses located on the fault trace were wrecked by the right-lateral displacement of 30 to 50 centimeters. On the other hand, the wide spread damage zone of several hundred meters appeared in Iruma where the village is located on artificial fill more than 6 m in thickness. Although many houses suffered damage such as falling walls or falling roof tiles caused by strong shaking, no serious damage, such as the linear concentration of wrecked houses, occurred on the estimated fault trace in Iruma.

In the northern part of Awajishima, the damaged area did not obviously correspond to the trace of the earthquake fault in the microscopic viewpoint. The collapsed houses are remarkable in the village located on the alluvial plain along the coast of Seto-naikai. The damage distribution seems to strongly reflect the weakness of the ground condition.

Thus, many cases derived from previous fault movement suggest that there is no evidence that the zone above the fault trace suffers more severe damage than areas a little distance from the fault from a microscopic viewpoint. It is a current and important problem that people, including fault researchers, are assuming that places on the fault trace line are the most dangerous without regarding the regional differences in ground conditions.

What is the dangerous aspect of an active fault ?

The Japanese Islands, a part of the Eurasian Plate, have been strongly affected by the E-W compressional stress associated with subduction of oceanic Pacific and Philippine Sea Plates. The compression has resulted in various types of deformed structures such as faulting and folding in the Quaternary. The active faults, which have a potential of future activity deduced from the repetition of faulting in the Quaternary under the present stress field, have accumulated geological and geomorphological displacement, and have resulted in the lowlands or plains in the relative subsiding side of the faults. Therefore, the trace of active faults tends to accord with large-scale geomorphological boundaries such as between mountains and basins, mountains and plains, and hills and plains. The Nojima fault in Awajishima has also formed the geomorphological boundary between the hills and mountains. The earthquake fault associated with the Hyogo-ken Nanbu Earthquake appeared exactly on the boundary.

The plains and basins formed by fault movement are important flat areas in the mountainous Japanese Islands, and have been exploited by people as places for productive activity. In other words, it seems that the active faults restrict the border of plains and basins in Japan. Therefore, the active faults frequently intersect the various kinds of lines such as railway, highway and communication lines connecting cities located on each basin and plain. Especially, due to the economic efficiency, the lifelines for the nation, that is the Shinkansen (Bullet train line), superhighways, and trunk communication lines linking the Tokyo, Hanshin, and Kyushu areas, are concentrated excessively along the Pacific coastal region of the main island of Japan. Several major faults intersect these lines in the Pacific coastal region. When these national lifelines are broken by fault activity and suspended functionally for a long period, the social and economic confusion in Japan affects not only domestic but also the international economy and political conditions. The long term suspension of the Shinkansen and Hanshin Superhighway line, which were broken by the Hyogo-ken Nanbu Earthquake, not only caused a delay in rescue and recovery in the damaged region but also interrupted the various kinds of communication between east and west Japan.

As mentioned above, the real hazard of the active fault is expressed in the following two points. One is that the active fault will cause severe seismic disaster through the occurrence of large earthquakes with shallow focus. The other is that the indirect and extended disaster will cause confusion to the social and economic systems as a result of the functional breakdown of the national lifelines.

4. How Can We Manage the Active Fault Successfully ?

How can we deal with the active faults that exist close to our communities ? We can examine the subject from the following two viewpoints. One is the regional management of active faults that might cause a large shallow earthquake in the future. The other is land use management on the trace of active faults.

How to manage an active fault which is expected to be the source of a large shallow earthquake in the future

We should make progress in long-term regional earthquake prediction based on hazard assessment of the individual active faults. The assessment is made by the reconstruction of recurrence intervals with the age of the latest event being extracted from geological, geomorphological, archeological and historical information. Especially, trench excavation, which digs a ditch across the fault trace and observes the geological units displaced by the fault movement, is the most effective method to extract the information on paleoseismicity recorded in the ground.

If the dormant time since the last event of an active fault is more than 50 % of its recurrence interval, the fault is estimated to have high potentiality of future movement and is called a marked active fault (Matsuda, 1977). As for these marked faults, it is necessary to promote various measures for seismic hazard prevention through simulation of the seismicity and hazard assessment.

However, hazard assessment of active faults is not yet technically established. Therefore it is difficult to carry out the assessment of every active fault indiscriminately. Although the faulting history can be reconstructed from the geological and geomorphological information concerning an active fault, it becomes more and more difficult to obtain information on faulting because of the the artificial modification of the ground surface accompanying urbanization.

It is necessary in the future to promote fault surveys from which it will be possible to obtain information on faulting through the conventional method. At the same time, it is also necessary to make an effort to develop new methods for the reconstruction of fault movement. On the other hand, the government should promote hazard assessment not only of those active faults having much data but also of the faults having a regional importance such as those neighboring a big city.

The land-use management on the fault

As for the site location of nuclear power plants, it is important that the facilities be kept away from active faults. When a nuclear reactor is constructed, the rock body beneath the reactor is strictly examined to determine whether a fault or crack exists in the rock. The maximum magnitude of an earthquake which is expected to occur from an active fault near the power plant site is also considered in the designing of the earthquake-proof-structure for the nuclear facilities.

The author thinks that it is reasonable to keep nuclear facilities from active faults since damage to a reactor would have severe domestic as well as international impact. However, is it reasonable to apply this same land-use management to normal buildings as well as to nuclear facilities? In fact, some foreign countries have regulated land-use on active fault traces. The Alquist-Priolo Special Studies Zones Act was promulgated in California in 1972. Alquist and Priolo are the names of congressmen who proposed the act. The main points of the spirit and content of the law are the following (Nakata, 1990).

The first is that the state government can designate Special Studies Zones (SSZ) along the major active faults in California. The second is that when people make an application for new construction in the SSZ, the state government can approve the construction only after an examination confirms that the structure certainly avoids the trace of an active fault. The third, if a fault exists in the construction site, the government can control the construction to keep the structure more than 50 feet away from the fault trace.

This act aims to keep people safe from the breaking of structures due to fault displacement and to isolate our living place from the active fault. However, the act does not take damage by severe shaking into consideration.

There is an opinion that the Japanese Government should regulate land-use on the trace of active faults as is done in California. However, the author doubts whether such regulation is really effective for the prevention or reduction of earthquake hazards in Japan.

The records of shallow earthquakes show that the seismic intensity was the highest in the epicenter region and decreased toward the distal region of the seismic area when we consider the seismic intensity on a scale of a few kilometers (see Fig. 5). However, if we compare the direct damage by fault displacement in that area to the damage caused by strong motion in the area within several hundred meters from the fault, there was no difference in damage intensity between them (see Fig. 3). Therefore, there is no meaning in regulating the land-use of the extremely narrow zone along the active fault trace. Contrary to expectation, such regulation would be dangerous because it would put the people living outside the limited zone off their guard.

As a countermeasure against the proposed legal control along fault traces, the author proposes the necessity of opening information on the active faults to the public. Opening the information to the public indicates that the local government should provide the residents with information on the regional active faults such as their locations and the expected magnitude of earthquakes caused by them. This operation will produce the same effect as controling the land-use on the fault by law. If the public can get enough information on active fault traces, the people who are anxious about the potential damage caused by the fault break would never purchase real estate in that area. Therefore, the developer would never plan to build condominiums or housing complexes on the fault because of the difficulty in selling them. On the other hand, if the people judge the hazard of faulting to be less dangerous in the near future, they can build earthquake-proof-houses on the fault at their own risk.

The reason why the central government should carry out measurement of active faults is not to regulate the land-use of the narrow zones along the fault traces but rather to thoroughly open the fault information to the public and to promote preventive measures against the seismic hazards caused by recurrent movement of active faults. These measures include operations to maintain the national lifelines in case of a destructive earthquake. The construction of alternate routes for the national lifelines which cross active faults is very important in order to keep the social systems functioning. However, this will lead to an increase in cost for infrastructures and will give harmful effects to the nation's livelihood and economy. It will be difficult to maintain the alternate facilities for national lifelines under the independent profit system that is now adopted. To conquer the above mentioned difficulties, it is necessary to employ a policy with the viewpoint that earthquake prevention is one part of the national defense system as well as the military system.

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(*: in Japanese, **: in Japanese with English abstract)