Hazards from Surface Faulting in Earthquakes

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Abstract

Well-known earthquakes accompanied by surface faults since the 1891 Nobi earthquake are reviewed, and hazards from faulting are summarized. Morphology of the hazards as the offset of ground, grabens, mole tracks, tension cracks en échelon, gentle flexure or wavy swelling of land surface are described. Several examples of distribution of damage relative to faults shows that in earthquakes of M 7.0 to 7.5 the width of the endangered area where totally collapsed houses would exceed 30% would be 5.5 to 7.5 km in mountaineous regions and some ten kilometers in alluvial plains. Dimensions and other features of faults are investigated and the region at risk due to faulting is discussed. The horizontal displacement is predominant in most earthquake faults in Japan. Plural faults generally move in an earthquake, and a belt 0.4 to 3 km wide on both sides of a postulated fault as well as conjugated faults crossed by the latter are at risk.

1. Introduction

Surface faulting in earthquakes has caused severe damage in source regions of large earthquakes. The hazards from it, however, have not been paid much attention to in Japan, while in the United States and other parts of North America the problem has been often treated and criteria for establishing Risk Zones or designing related to faulting are discussed actively[1),2),3),4)]. The state of affairs in Japan does not necessarily imply unimportance of the problem for this country, but seemingly has been caused by the fact that a disproportionaly small fraction of earthquakes have produced on-land surface faults because of the geographical condition of being surrounded by the Oceans and Seas.

However, the situation is changing rapidly, because important structures must be planned at sites of increasingly unfavorable natural as well as social conditions, and as a consequence potential hazards from active faults may sometimes become critical in relation to choosing the site of those structures or on other similar occasions. The assessment of activity of a specific fault can be conducted by means of geological, geodetical, seismological, or other various procedures, but unfortunately most man-made structures cannot be evacuated from a site even if a destructive earthquake would be predicted at the site. Thus, it is necessary and the only possible way for us to prepare for the effects of postulated faulting. And for the purpose of sufficient planning or designing against active faulting it is indispensible to acquire knowledge of accompanying phenomena.

The purpose of the present Paper is to summarize experiences in earthquakes accompanied by faulting since the Nobi earthquake 1891 and on the basis of the summary to discuss problems as the morphology of hazards, the distribution of damage, the dimensions of and the risk zones around faulting, etc.

2. Summary of Earthquake Faulting Since 1891

Nobi Earthquake in 1891; Faulting in the Nobi earthquake is described by Matsuda[5] in detail. The main fault segments from north to south are the Nukumi fault of about 20 km from Nojiri to the Nukumi pass, the Neodani fault of about 35 km from the south of Mt. Hakusan to the east of Kawauchi, and the Umehara fault of about 25 km from the north of Ikehara to Yanagibora, which formed an aggregated main fault system of about 80 km long with a trend of NW-SE. Besides the above, several faults of shorter extention as the Kurotsu, Midori, Midori-Daishogun, and Koze faults exist (Fig. 1).

The senses of horizontal slip were consistently left lateral, however those of vertical offet were mostly SW-side uplifted excepting a part of the Nukumi fault and the Midori fault. The amounts of slip were in general greater in horizontal than in vertical yielding 3.0 m(H) and 1.8 m(V) in the Nukumi fault, 8.0 m(H) and 4.0 m (V) in the Neodani fault, and 5.0 m(H) and 2.4 m(V) in the Umehara fault, respectively. It is noted, however, the maximum vertical offect 6.0 m appeared at

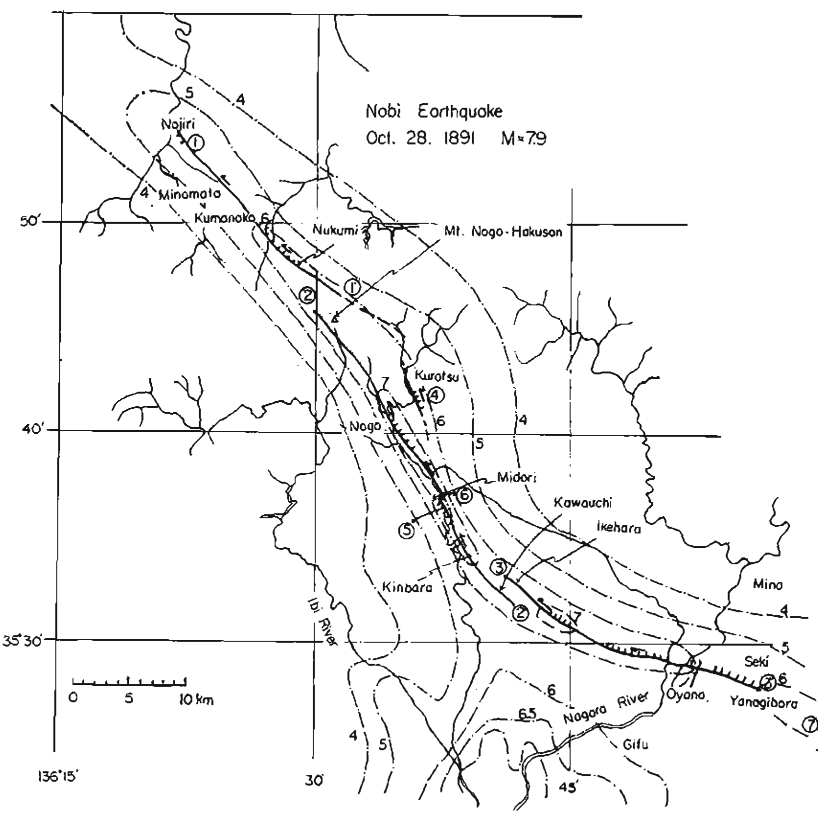

Fig. 1. Faults and earthquake intensities in the Nobi earthquake; ①; Nukumi fault, ②; Neodani fault, ③; Umehara fault, ④; Kurotsu fault, ⑤; Midori fault, ⑥; Midori-Daishogun fault, and ⑦; Koze fault. (compiled after Matsuda and Muramatu)

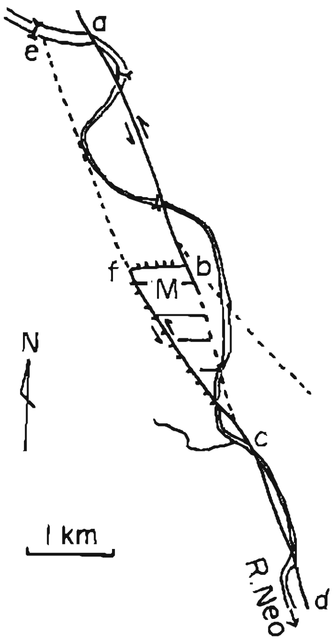

Fig. 2. Triangular bulge at Midori due to left-lateral movement on the main fault in the Nobi earthquake; a-b-c-d; Neodani fault, e-f-c; Midori fault, and b-f; Midori-Daishogun fault. (illustrated after Matsuda)

the Midori fault with 4.0 m(H), where in contrast to cases in most of the main fault segments the NE side was uplifted. This peculiar phenomenon may be attributed to a bulging due to compression accompanying the left lateral shear of a triangular block bounded by the Midori fault (N40W), the Midori-Daishogun fault (nearly EW) and the main fault of Neodani[5] (Fig. 2).

In Fig. 1 it may be noted at once that the three main fault segments do not constitute a simply connected line, but there are gaps of about 3 km and 1.5 km between the ends of the Nukumi fault, the Neodani fault, and the Umehara fault in turn, and also that the mean strike of the main fault line changes from N45°W in the northern part to N60°W in the southeastern Umehara fault. Nasu[6] estimated a hidden, i.e. sub-surface fault named Line C based on the result of levelling at triangular points. Muramatu[7] also suggests a concealed fault line from Kinbara through north Gifu and Ichinomiya to Nagoya on the basis of data of seismic intensity and crustal deformation, which line deflects to some extent eastward from the line C.

Shonai Earthquake in 1894; On the occasion of the earthquake, Koto[8] visited the site convinced of the cause to be faulting. His intuition originated from his experiences of the Nobi as well as the Kumamoto earthquake in 1894, where he suppoited the fault-origin hypothesis rather successfully. Koto determined faulting which extends from Oishi 16 km east of the Sakata harbor north-eastward through Yadaresawa valley, after which the fault was named, to Ôdaira (Fig. 3). The strike of the fault was around N55°E and its south side was uplifted without horizontal slip being observed. Further extension was not clear, but Koto assumed a fault line through sites of severer damage, Ôwarabi, Shimoaozawa, Wakamiko, Sôda, Sumo-

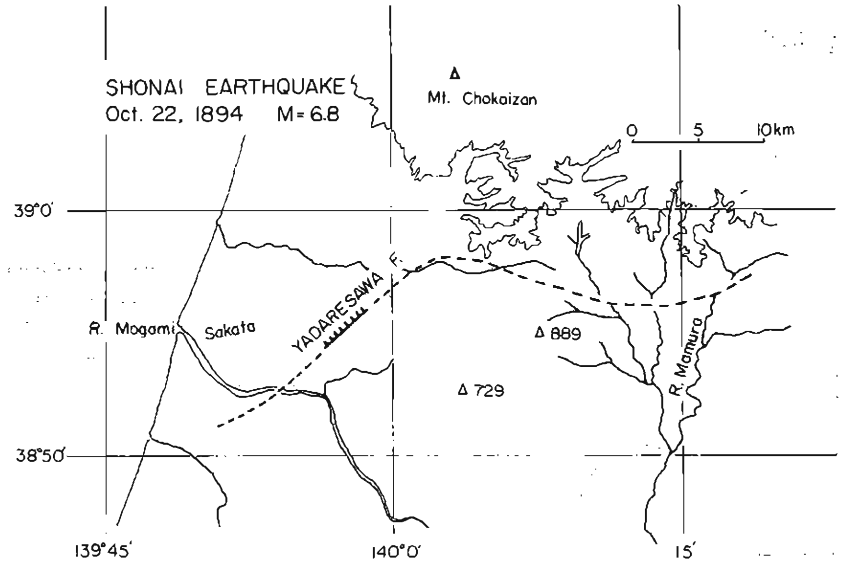

Fig. 3. Faulting in the Shonai earthquake. The broken line is postulated.

modai, and Ôashizawa. Further, there were many slope failures and cracks on the south slope of the pass to Masuda along the Nikkogawa river. Koto did not investigate more easterly region by himself, but requested it a Mining Engineer, K. Sugaya.

On the other hand the fault becomes unclear to the west of Oishi, because the bedrock is covered by alluvium. Koto assumed a fault line lying through Oishi, Kôriyama, Sakurabashi, Tenjindo, midway between Nîbori and Ochinome and reaching to the vicinity of the Kuromori dune based on high frequency and the predominance of NE-SW direction of fissuring.

The above concealed part to the west and the postulated part for the more easterly region than Aosawa on the basis of a report on the damage by Sugaya are drawn in broken line in Fig. 3 In Table 1 the length of the Yadaresawa fault is given as 10 km, which corresponds to the part from Nîbori to Kita-Aosawa. In conclusion it seems to be doubtful if faulting actually occurred in the Shonai earthquake, or at least it must be stated that not much is known so far on the faulting in this earthquake in view of available materials.

Rikuu Earthquake in 1896; Two nearly parallel faults were formed in the earthquake; the Kawafune fault and the Senya fault (Fig. 4). The former is a reverse fault with its west side uplifted which was formed along the Wakadani valley on the east side of the Mahiru mountain ridge of NS trend. At the northern end of the fault, Ôaresawa in the Wakadani valley, it exhibited a vertical offest of 2 m, and extended southward through Wakahata, Yatsumata, Kôge, Kawafune, where also the west sides were uplifted by the order of 1 to 2 m, and further somewhat indistinctly toward the west of Ôta reaching about 15 km in total length. It is interesting to note the manner of faulting at Kawafune, where a road was crossed by the fault

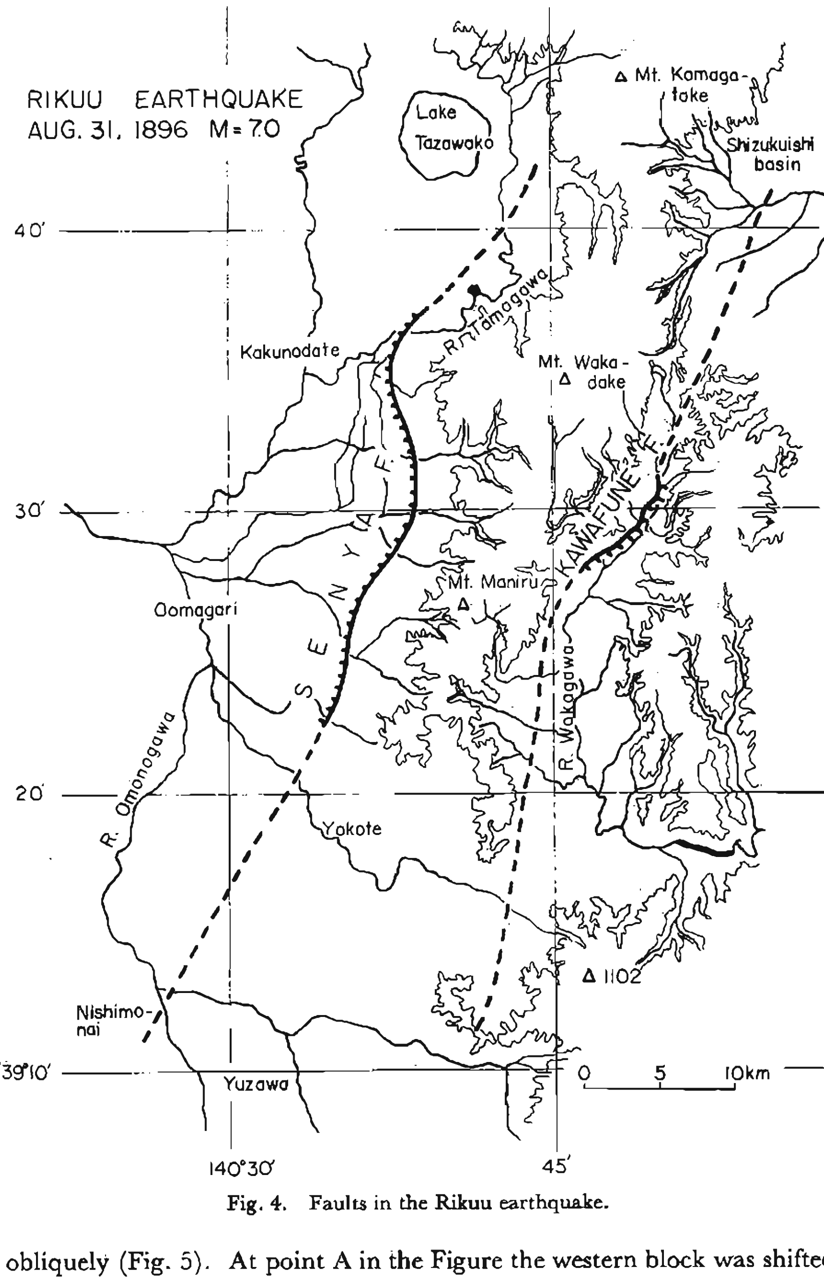

Fig. 4. Faults in the Rikuu earthquake.

twice obliquely (Fig. 5). At point A in the Figure the western block was shifted more than 1 m eastward as well as upward relative to the eastern block. To the south of Kawafune, where the fault ran on the western side along the road, the latter was buried entirely by soil because of reverse faulting and landsliding. Yamasaki[9] assumed a further extension of the fault southward based on the concentration of severer damage lying through Ecchuhata, Kurosawa, Mitsumata, and Tagonai. Likewise, he postulated an extension also to the north as far as the Shizukuishi basin. These postu-

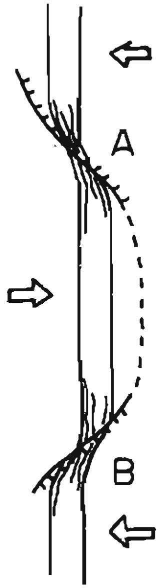

Fig. 5. Thrust movement on the Kawafune fault in the Rikuu earthquake. (illustrated after Yamasaki)

lated parts are given in broken line in Fig. 4.

The Senya fault was formed from Obonai southwestward through Mukô-Obonai, where the east side was uplifted generally by about 2 m, disappeared for a while, then later reappeared at Hirokunai with 1 m vertical offset, and extended further through Shiraiwa, Kurisawa, Ôta, Kurosawa, Senya, Rokugô-Higashine, where also the east side was uplifted generally by 1.5 to 2 m and even to nearly 3 m at Senya, and finally to the north of the village of Kanazawa. The fault becomes indistinct, however Yamasaki again postulated an extension through Asamai 1 km west of Yokote, Mutsuai, Sugimiya, and Kaizawa. The length amounts to 25 km, if one takes the part from Shiraiwa to Kanazawa, while it reaches 60 km from Obonai to Asamai. This fault also is considered a reverse fault with little horizontal shift.

Yamasaki considered the Senya fault as a probable northern extension of the Yadaresawa fault in the Shonai earthquake of two years before. He noted the coincidence of the uplifted sides, SE blockes, in the both events. It is noted also that frequent foreshocks preceded the earthquake since 23, August until the day of the main shock, 31, August 1896. In this context the Shonai earthquake may have actually been related in some way to this earthquake, as supposed by Yamasaki.

Kanto Earthquake in 1923; The main fault or the Sagami-Bay fault has been assumed as the origin of the earthquake as early as 1928 by Yamasaki, Imamura[10], and others, which was recently demonstrated as correct on the basis of geodetical as well as seismological data[11),12]. According to the recent model it is a reverse right-lateral fault on a plane dipping 30 degrees towards NE with the dimension of 85 km long and 55 km wide (Fig. 6). Many faults observed on land after the earthquake are not the main but branch or secondary faults*, and they are classified into group

* Definitions by M.G. Bonilla[31] are followed (See. Fig. 20)

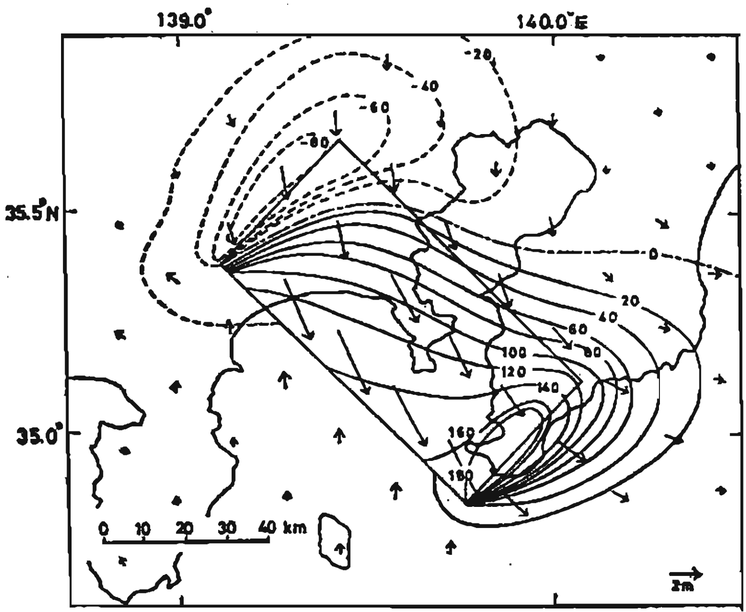

Fig. 6. The causative fault in the Kanto earthquake dipping 30° toward N.E. Solid lines denote upheaval, broken lines subsidence, and arrows horizontal shifts, respectively. Numbers imply amounts in centimeters. (original draft by Kanamori and Ando; reproduced from Sugimura)

A and B by Sugimura[13]. Accordingly, group A includes the Shitaura, Boshu (Enmeiji, Uto, Takigawa), Hatsushima, Yatsuka, Hota, Kamogawa, Hakone, Nebukawa and Sakawa faults, and group B the Shinkawa, Tanzawa, Susugaya, Sakaigawa, Negishi, and Renkoji faults, where group A is for faults nearly parallel to the Sagami-Bay fault and group B is for those of irregular strikes found generally in northern areas, which exhibited subsidence or upheaval of smaller amounts less than 100 cm. Most aftershocks occurred in the B-group region.

It is interesting to note that Imamura[10] considered the earthquake to be of the multiple-shock type, in view of the complicated seismograms of the main shock and many faults found on the land. He assumed the first origin at the bottom of the Sagami-Bay, the second at the Tanzawa region, and the third again in the Sagami-Bay off Odawara. It tells that a 'region' rather than a 'line' or a 'point' was considered as the source of an earthquake already as early as 1920th.

Tajima Earthquake in 1925; Two faults parallel to each other, the Tai West as well as Tai-East faults, were formed (Fig. 7)[14]. The former was 0.7 km long and the latter about 1.6 km long, and the distance between them was 400 m. The Tai-West fault ran from the cliff facing the Tsuiyama bay towards NW, with several fissures. It appeared on the mountain as a concentration of some ten fissures, which formed as a whole a graben-like depressed zone. The west side of the fault was subsided, however some fissures exhibited hinge-fault movement. The East fault

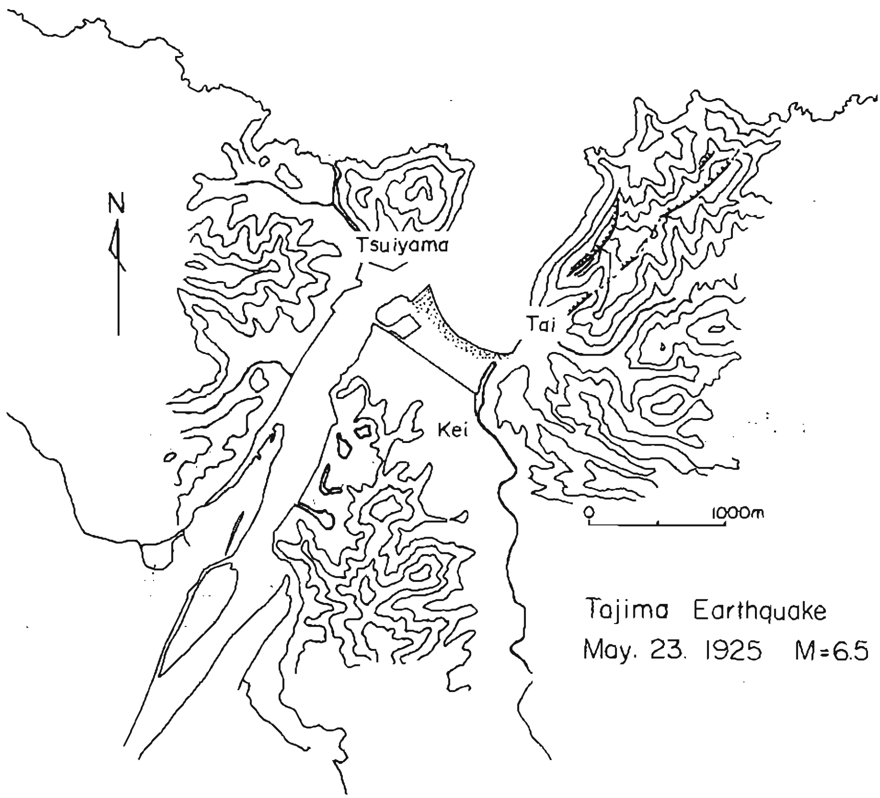

Fig. 7. Faults in the Tajima earthquake.

appeared behind the village of Tai and passed near the triangulation point 231.2 m and ran toward NE. The number of fissures was less than that of the West fault, but the downward movement of the west side against the east side was very distinct amounting to 60 to 85 cm and sometimes even 1 m. The both faults are parallel to the cliff of the Tsuiyama bay and the mode of displacement is westside down coincident to the case of the cliff. The horizontal offset could not clearly be determined in both of these faults.

Tango Earthquake in 1927; The Tango earthquake is characterized by a pair of very peculiar conjugate faults called the Gomura fault and the Yamada fault[15]. The former crossed the Tango Peninsula from NW to SE, and the latter ran along the southern coast of the Peninsula from SW to NE composing a conjugate pair with the former (Fig. 8).

The Gomura fault consists of the following segments in échelon arrangement; 1) the Takahashi fault of about 8.9 km with strike N30°W to N15°W; 2) Nimbari fault of 2.4 km, N8°E; 3) the Nagaoka fault of 3.75 km, N30°W, which constitute as a whole a 18 km long aggregate main fault system with a strike of around N30°W and a probable dip of 70° towards SW, i.e. SW side upthrown.

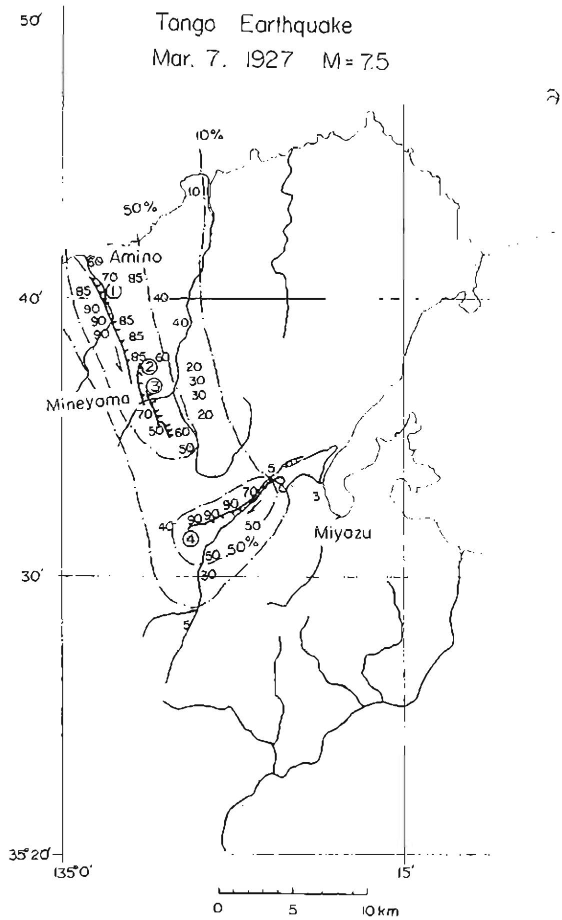

Fig. 8. Faults and percentages of totally collapsed houses in the Tango earthquake; ①; Takahashi fault, ②; Nimbari fault, ③; Nagaoka fault, above three together named the Gomura fault, and ④; Yamada fault.

It is a left-lateral fault (max 260 cm) with always the SW side upthrown.

The approximate strike of the Yamada fault is S55°W-N55°E. It is right lateral (max 40 cm) with NW side upthrown. The Shiroyama tunnel of JNR was traversed by the Yamada fault and the south-side wall of the concrete lining has shifted westwards relative to the north-side wall.

Kitaizu Earthquake in 1930; Faults in this earthquake are described by Matsuda[16] in detail and tabulated in a standard form. Predominant ones in these are 1) the Hakonemachi, 2) Tanna, 3) Ukihashi-Central, 4) Ukihashi-West, 5) Ôno, 6) Kadono, and 7) Himenoyu faults. It is noted that there are left-lateral faults of NS trend as well as conjugate right-lateral ones of N60°–70°W strikes. The members 1) to 6) are the former and 7) and other minor faults as the Baragataira fault,

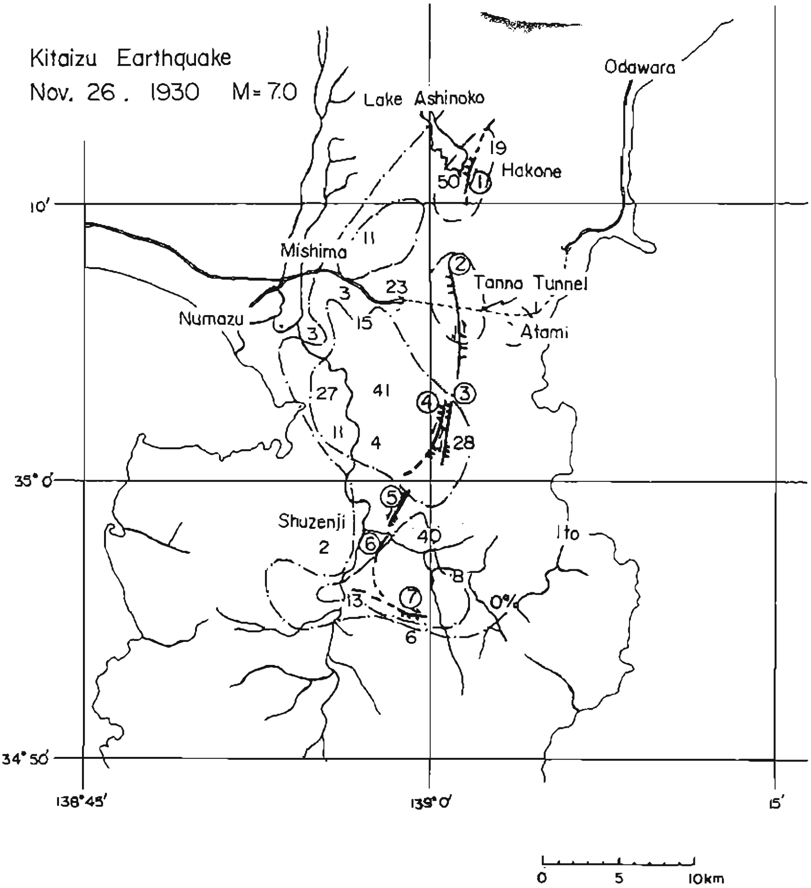

Fig. 9. Faults and percentages of totally collapsed houses in the Kitaizu earthquake; ①; Hakonemachi fault, ②; Tanna fault, ③; Ukihashi-Central fault, ④; Ukihashi-West fault, ⑤; Ôno fault, ⑥; Kadono fault, and ⑦; Himenoyu fault.

etc. are the latter (Fig. 9). Each fault constituting the main fault system is formed in échelon arrangement with gaps between each end of 1 to 5 km in the direction of strike and 1 to 2 km in the direction perpendicular to the strike. The amounts of offset across faults were 0.3 to 3.5 m in horizontal and 0.2 to 2.4 m in vertical direction. In contrast to a consistent sense of slip in horizontal component the vertical ones at faults of NS trend were variable, and especially the Tanna, both Ukihashi, Ôno, and Kadono faults proved to be hinge faults, i.e. the east sides were uplifted in the northern parts and the west sides in the southern parts, while the movements were consistently left lateral in the horizontal component. According to Kuno[17] the west side should be uplifted in the southern part and its extension of the Tanna fault, but it was not very distinct in this earthquake. In Karuizawa in the Tanna Basin the drying up of wells and a strange phenomenon, where radishes were thrown out of soil are reported[18]. The Tanna tunnel, JNR, under construction suffered damage

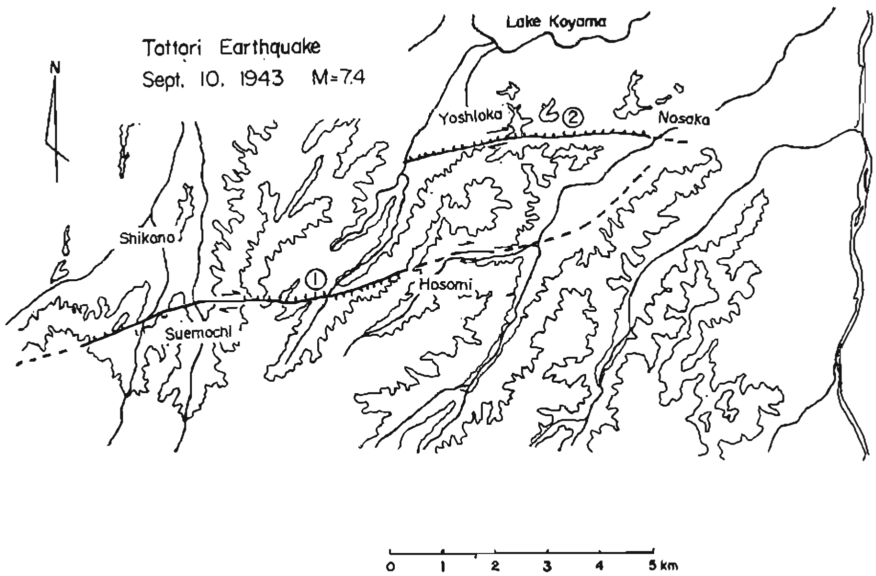

Fig. 10. Faults in the Tottori earthquake; ①; Shikano fault, and ②; Yoshioka fault.

due to faulting to be described later.

Tottori Earthquake in 1943; Two faults nearly parallel with each other, both of almost EW trend, i.e. the Shikano fault of 8 km long and the Yoshioka fault of 4.5 km long were formed (Fig. 10)[19,20]. The former lies from Suemochi to Kuchi-Hosomi and exhibits a right-lateral slip amounting to 1.5 m in the maximum. As for the vertical displacement, the south side was uplifted in the western half, while the north side was in the eastern half, thus forming a so-called hinge fault. The dip of the fault plane is estimated as 60° to 70°N.

The Yoshioka fault is 4.5 km long lying from Nagara to Nosaka and the south side is consistently upthrown at the maximum of 0.5 m with a dip of nearly 90° or slightly less toward S. The horizontal offset amounted to about 0.9 m in a right-lateral dislocation manner. Thus, the fault is considered as a reverse transcurrent type.

The positions of the two faults are en échelon, and it cannot be determined which may be the main or the secondary, since they have comparative lengths and displacements. The normal distance between the both faults is about 2 km, however it is also possible that they join together underground near Nosaka (See Fig. 10).

Mikawa Earthquake in 1945; Two very peculir faults were formed in this earthquake, i.e. the Katahara fault or the Fukôzu fault and the Yokosuka fault (Fig. 11). The former has been described by Tsuya[21] in detail. It starts at the right bank of the Otowagawa river in Katahara town toward north, bends to west at Maeno and extends as long as about 500 m, turns there NNW and goes 2.75 km as far as Fukôzu, and there again turns to the West and proceeds along the Sakagawa river on the north

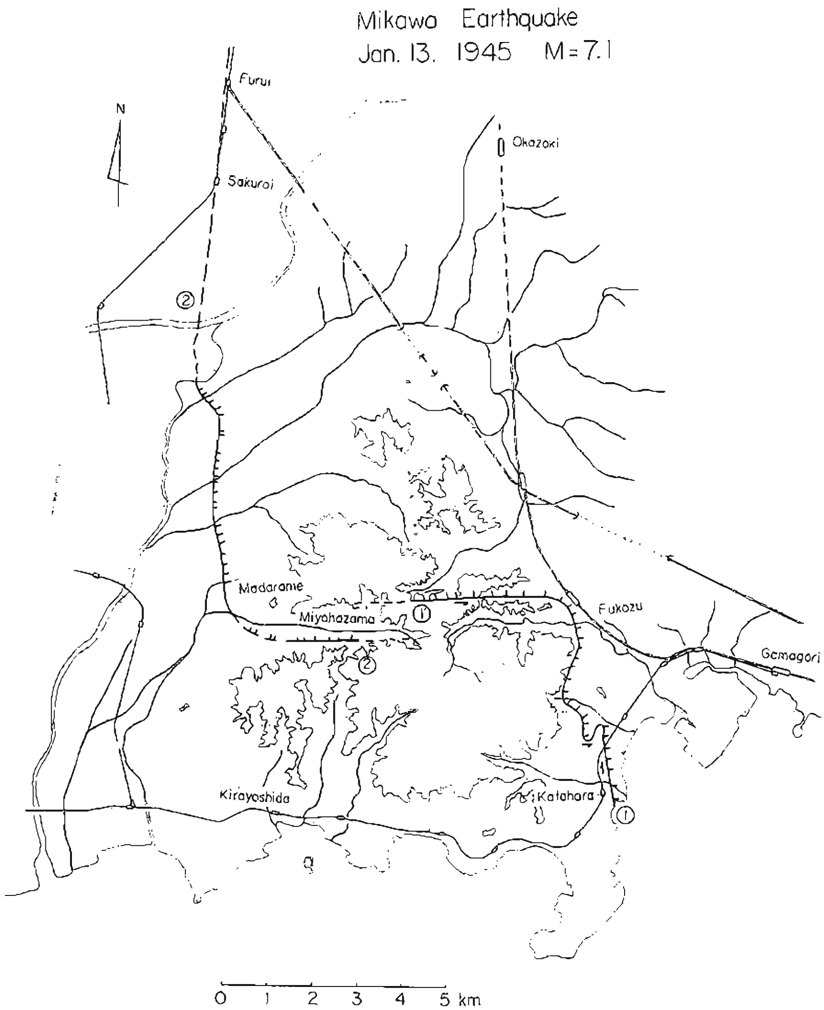

Fig. 11. Faults in the Mikawa earthquake; ①; Fukôzu fault, and ②; Yokosuka fault.

bank for about 3.5 km, and disappears NE of Miyahazama, constituting a surface rupture of 9 km in total length.

The Yokosuka fault appears south of Miyahazama and extends westward amlost parallel to the northern wing of the Fukôzu fault with the distance of about 800 m to the south of the latter as long as a little more than 2 km, turns there to the North and extends via Madarame, east of Kezôji, Takagawara and Ehara to the neighborhood of Ojima. The fault disappears there once, but reappears about 600 m to the west, i.e. at Shikoya, and it extends again northward via Fujii and Sakurai, and probably reaches to a point about 1 km east of the Anjô station of the Tokaido line, JNR. The position of the Yokosuka fault is somewhat ambiguous because insufficient references are available[22),23)].

The both faults described above have NS as well as EW wings. In the Fukozu fault the NS wing exhibited right-lateral slip of about 0.5 m with the west side uplifted by 1.0 m, and the EW wing left lateral of 1.3 m with south side uplifted by 2.0 m. From the mode of displacement the two wings may be considered to be a conjugate pair, however a thrust movement is predominant. It does not contradict the result of levelling, which reveals an upheaval amounting to 1.1 m at the Inou harbor in Nishiura 1 km south of Katahara[23].

In contrast to this it is said that the NS wing of the Yokosuka fault was left

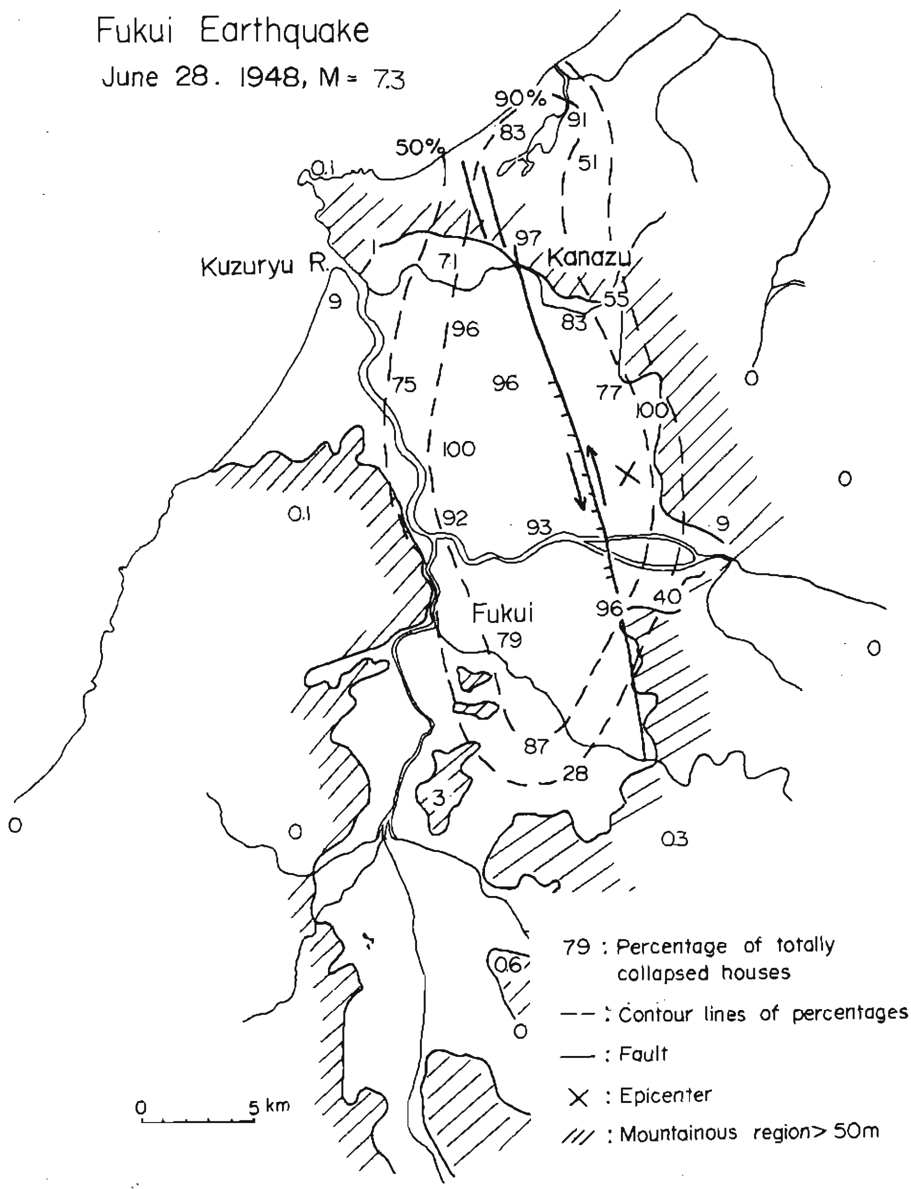

Fig. 12. The underground fault and percentages of totally collapsed houses in the Fukui earthquake.

lateral with horizontal slip of the order of 0.2 m with west side uplifted by 1.2 m, while the EW wing was left lateral of 0.4 to 0.6 m with south side uplifted by 0.4 to 0.5 m[22]. The mode of left lateral of the NS wing of the Yokosuka fault is strange considering the mode of thrust of the Fukozu fault, and that part of the description of the Yokosuka fault is probably incorrect.

Fukui Earthquake in 1948; Faulting in the Fukui earthquake was not a surface faulting in a proper sense, but it was presumed through data of levelling and triangulation (Fig. 12)[24]. Soon after the earthquake the measurments were carried out and an upheaval and northward displacement of the eastern half of the Fukui plain as well as a subsidence and southward displacement of the western half were detected. The maximum dislocation were estimated as 70 cm in vertical and 230 cm in horizontal. The boundary between the uplifted and subsided regions ran N20°W–S20°E. The total length of the fault amounted to about 25 km and its northern end reached the coast of the Japan Sea. Numerous fissures and cracks were observed on the ground surface above the fault line, however the main fault rupture itself remained

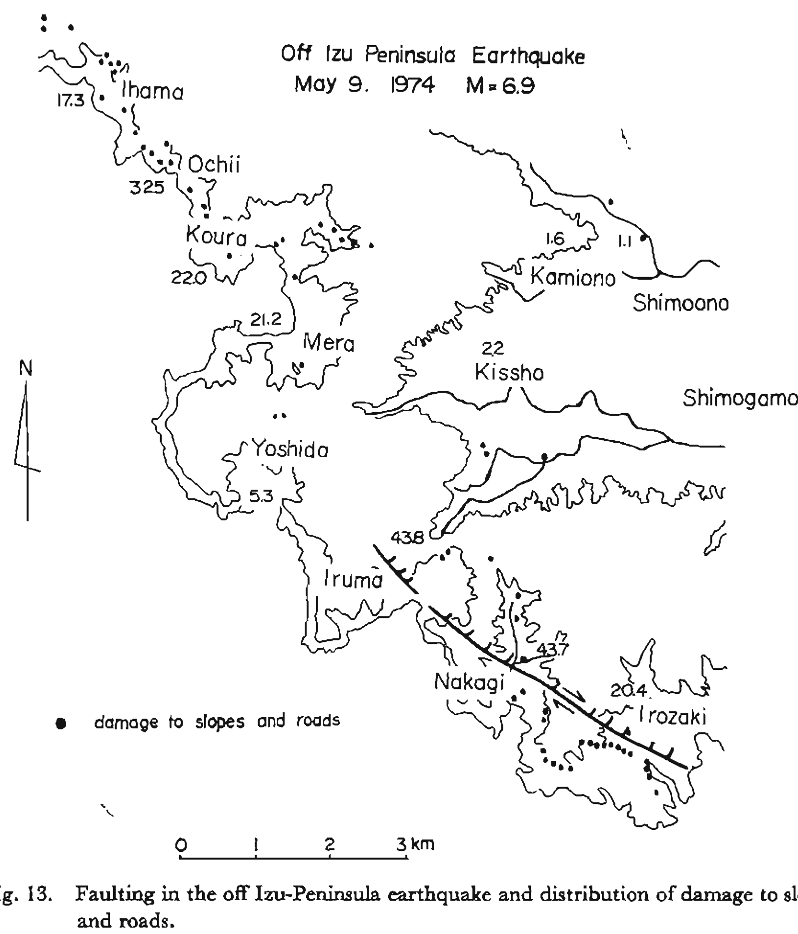

Fig. 13. Faulting in the off Izu-Peninsula earthquake and distribution of damage to slopes and roads.

concealed. They struck in general to north-south direction and were mostly as short as 10 m.

Two more segments of faults are reported[24] near the north end of the main fault zone: The first lies at the western part of Lake Kitagata and the second between Bandono and Ieyoshi, both striking NNW-SSE. The former may be a branch fault and the latter a secondary in Bonilla's sense[30].

Off Izu Peninsula Earthquake, 1974; In the earthquake of M 6.9 an evident right-lateral fault named Irôzaki-Central fault was formed traversing Irôzaki with a strike of NW-SE (Fig. 13). The fault appeared as a clear cut with an offset of 35 cm in horizontal and 17 cm in vertical at an andesitic rock cliff at the east end of the town. It traversed that locality forming en échelon fissurring, which caused breakage of many foundations of houses, crossed a road causing a slope failure, and extended toward NW in the mountainous region. It seems to have passed marginally the mountain side of the road connecting Irôzaki with other western sites at the point above Nakagi, destroying a tunnel on the road. After crossing this road at NW of the tunnel the fault extended further toward NW and became indistinct in the mountains.

The fault caused much damage to houses at Irôzaki as described above, while its probable effect on the notorious landslide at Nakagi, taking 27 lives, has also been discussed.

Besides the above main fault, Matsuda[25] describes the Irôzaki-North, Irôzaki-South, as well as Koura faults. They may be secondary faults in Bonilla's sense.

3. Morphology of Hazards from Faulting

A horizontal as well as vertical offsets of ground due to faulting are one of the important causes of damage to structures astride the faults. Small displacement along faults may be sufficiently destructive for certain types of buildings with a low ductility. More ductile structures can endure a certain amount of differential displacement, but no such structures are imaginable that will endure without serious damage a dislocation as great as 8 m, which occurred in the Nobi earthquake.

A typical example of damage due to relative displacement across a fault is the case of the Fukui earthquake, where an electric-power-line tower was bent at its legs towards NNE as a result of a pulling force through wires probably produced by a differential horizontal movement of ground across the fault.

The tunnel is a relatively earthquake-resistant structure excepting the portal, but it also cannot resist faulting and there are several cases where tunnels suffered damage due to faulting. An example is a very peculiar case in the Kitaizu earthquake where the Tanna tunnel of the National Railways, just having been driven, was traversed by the Tanna fault and the heading of a drain drift in the western pilot tunnel was lost because of a nearly horizontal displacement as great as 2.7 m. Another case is a railway tunnel at Shiroyama in the Tango earthquake, which was crossed by the Yamada fault and damaged severely. The Senzoku railway tunnel also was damaged badly at its portal as well as its inside lining by faulting in the Fukui earthquake.

The height difference caused by faulting on both sides of a fault also may cause inconvenience by impeding the flow of water. Such cases have been experienced in the Nobi, Rikuu, Mikawa, Fukui earthquakes, etc., where faults with dislocations with a vertical component were formed along or across rivers.

Besides those types of hazard described above there are various phenomena as grabens, mole tracks, tension cracks en échelon, gentle flexure or wavy swelling of the land surface, etc. The Tai-West fault in the Tajima earthquake, penetrating Tertiary tuff, caused a stepped graben 30 m wide, where some tens of nearly parallel cracks of 20 to 30 cm opening were observed. The Shikano fault in the Tottori earthquake also formed a graben-like depressed zone 1 m wide at a hill of weathered granite.

In soft soil areas cracks en échelon are observed very often (Fig. 14). This type of crack has been experienced in the Tango, Tottori, Mikawa, and the Izu-Peninsula earthquakes. They occur mostly in soft sediments and sometimes also in soft rocks.

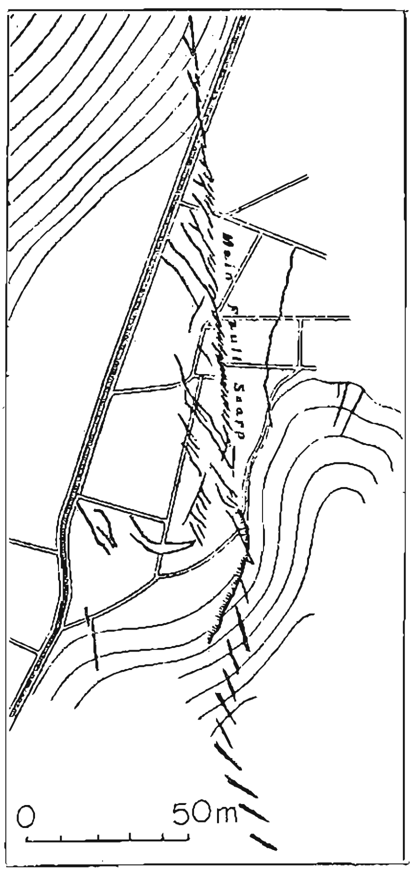

Fig. 14. Cracks en échelon along the left-lateral Gomura fault in the Tango earthquake. (reproduced from Yamasaki)

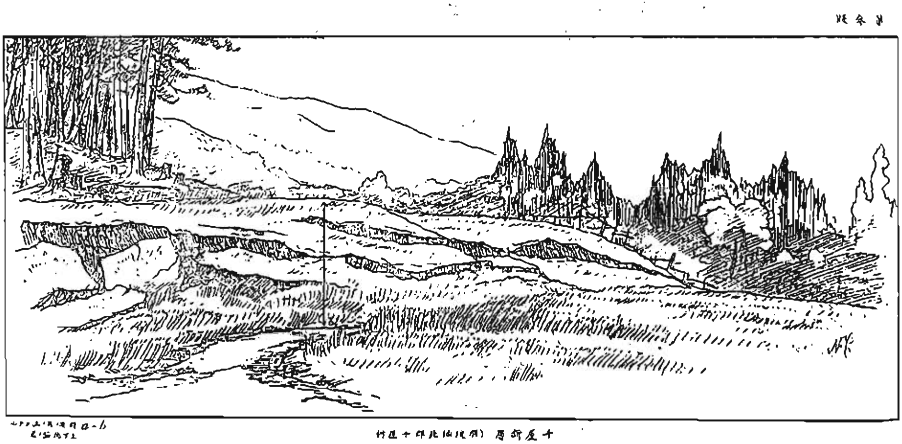

Fig. 15. Mole tracks along the Senya fault in the Rikuu earthquake. (reproduced from a sketch by Yamasaki)

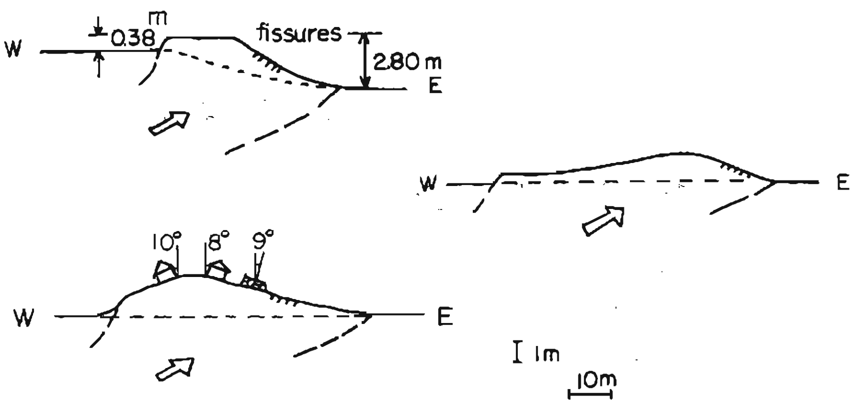

Fig. 16. Mole tracks along the Fukôzu fault in the Mikawa earthquake. (illustrated after Inouye)

In the Tango earthquake a series of cracks en échelon as shown in Fig. 14, were formed along the left-lateral Gomura fault. It is evident that these cracks were caused by tensile stress due to shear. In the Tottori earthquake also a series of cracks with strikes N50°–80°W were observed along the right-lateral Shikano fault in the EW direction, which also suggests the same cause of these cracks.

Mole tracks along the intersection of a reverse fault with the ground surface are also observed very often, e.g. in the Nobi, Rikuu, Tajima, Tango, Mikawa earthquakes, etc. They occur in general in soil or soft rocks, while in hard rocks a fault appears as a clear cut. An appearance of the phenomenon along the Senya fault in the Rikuu earthquake is reproduced from a sketch by Yamasaki (Fig. 15). This phenomenon was especially remarkable in the Mikawa earthquake, where a zone 40 to 60 m wide was upheaved, causing a height difference up to 2 m between the both sides of the zone (Fig. 16). Houses and other structures on the upheaved zone were inclined up to about 10 degrees. A wavy swelling or gentle flexure of the ground

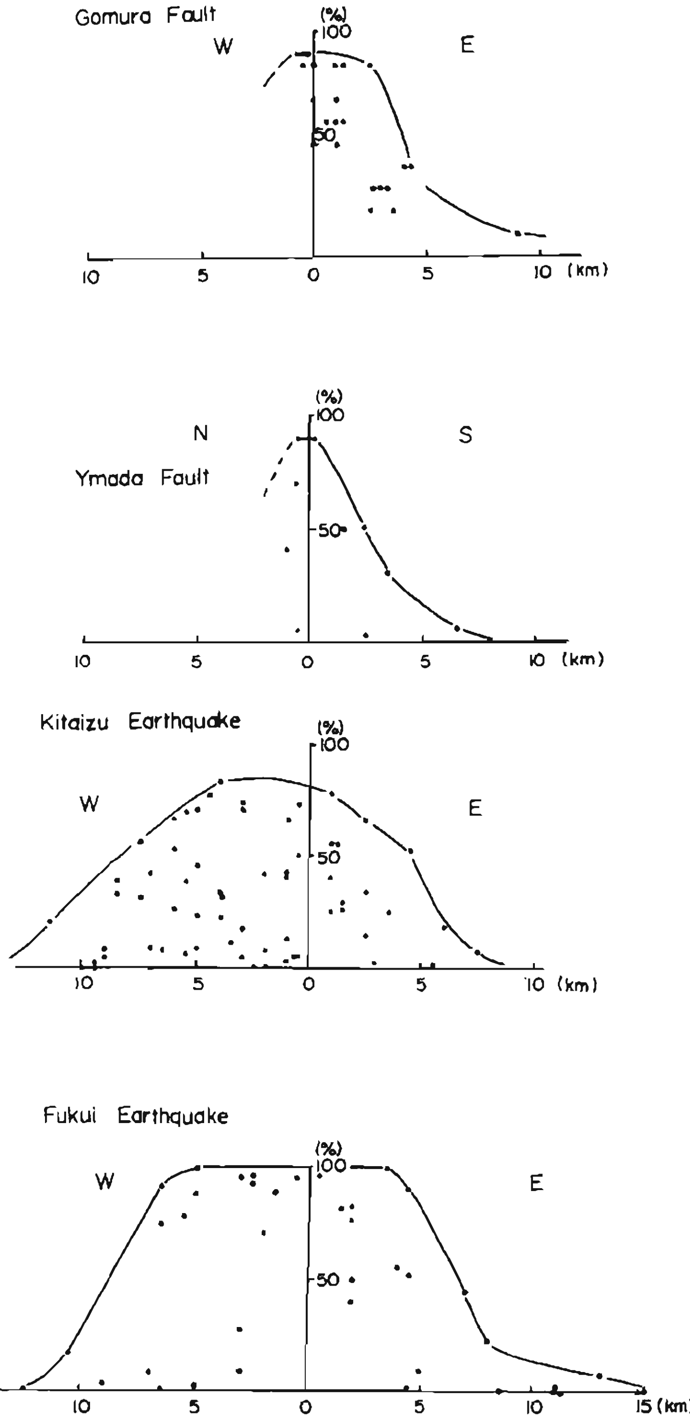

Fig. 17. Percentages of totally collapsed houses versus distance from the fault line in the Tango (M=7.5), Kita-Izu (M=7.0), and Fukui earthquake (M=7.3).

surface, which seems to be an incipient stage of the mole track, was reported at the Gomura fault in the Tango event.

4. Distribution of Damage to Houses and Other Structures Relative to Faulting

Percentages of collapsed houses or earthquake-intensity scales are given in Fig. 8, 9, and 12. It is seen in these figures at once that the distributions of equal percentages or intensities are not concentric around an epicenter but oval surrounding the line of surface faulting. The fact is especially remarkable in the Nobi and Tango earthquakes. In Fig. 1 areas 3 to 5 km wide including the Nukumi, Neodani, and Umehara faults exhibit intensities higher than VI, excepting the northern end of the Nukumi fault. According to the correlation table by Muramatu[7], the lower bound of the intensity VI corresponds to 1 % of totally collapsed houses and 260 gals of ground acceleration.

The percentages versus the distance from the main faults in several earthquakes are illustrated in Fig. 17. The values drop rapidly with the distance from the fault. The distances yielding 30 % of totally collapsed houses, which is believed in general to correspond to the lower bound of the JMA intensity Scale VII, are 4.5 km in Gomura, 3.5 km in Yamada both in Tango, 5.5 km on the east side and 10.5 km on the west side of the Kita-Izu main fault system, and 7.5 km on the east side and 10 km on the west side of the concealed fault in Fukui. The difference in the distances on the both sides of a fault in the last two cases may be due to various ground conditions, since the east sides are mountainous in contrast to the west sides, including alluvial plains in both cases. Accordingly, it can be stated that in an earthquake of M 7.0 to 7.5 the width at risk of being exceeded by 30 % of totally collapsed houses would be 5.5 to 7.5 km in mountaineous regions and some ten kilometers in alluvial plains.

Recently, Omote et al.[26] investigated the distribution of overturned gravestones in the Central-Ōita earthquake of M 6.4 and estimated the maximum accelerations versus the distance from the latent fault postulated from the concentration of damage as shown in Fig. 18. In the figure it is evident that the maximum accelerations drop rapidly from about 5 km on. The result seems to meet the experiences described above.

It is often stated that the upthrown side or hanging wall experienced severer damage. Matsuda[5] refers to a greater drag of soil at Kinbara and Nukumi and heavier damage to the wall of a well just crossed by the fault at Itasho both in the west side, which was upthrown in the Nobi earthquake. According to Yamasaki and Tada[15] more tension cracks en échelon were observed on the south-west side of the Gomura fault than on the opposite side. Also in the Mikawa earthquake evidently heavier damage to houses or other objects such as grave stones, etc. on the uplifted south-western side is reported[22]. The reason may be at least partly a severer fracturing of fault wall on the upthrown side.

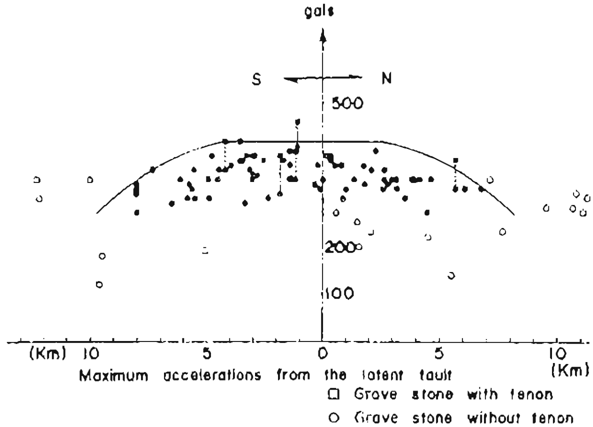

Fig. 18. Maximum accelerations versus distance from the postulated fault line in the Central-Ōita earthquake. (reproduced from Omote)

Facts suggesting a possibility for gentle process of faulting have often been reported. As an example objects on shelves did not fall at all in a farmer's house which was traversed by the Shikano fault in the Tottori earthquake[27]. In the Mikawa earthquake masonry lanterns on the mole track formed along the Yokosuka fault were inclined but remained standing[23]. Similar experiences can also be found in foreign literature[4]. In this connection an interesting tale by an eyewitness in the Nobi earthquake is introduced by Matsuda[5]. It tells that at least several to some tens of seconds had elapsed after the beginning of strong shaking until the Umehara fault, one of the main-fault segments, was formed.

In contrast to those described, there are naturally also evidences suggesting strong shaking near the causative fault, or in small epicentral distances. Such cases are reported in the Tango, Kitaizu, Tottori and other earthquakes.

5. Dimensions and Other Features of Faulting and the Region at Risk around Active Faults

In assessing hazards from surface faulting it is necessary to specify its parameters as to the position, the dimension, the mode and amount of displacement, etc. These parameters in past earthquakes excepting the position, which in essence should be predicted, may be useful in their nature in hazard assessment. Experiences related to dimensions, etc. will be described in the following:

The relation between the earthquake magnitude and the length of fault is given for faults in northern California and Nevada by Tocher[28] in the form

$$\log_{10}L\ (\mathrm{km}) = 1.02M - 5.72$$

Iida[29] derived a similar relation from data for the whole world as

$$\log_{10}L\ (\mathrm{km}) = 1.32M - 7.99$$

The data for Japan in Table 1 are plotted in Fig. 19, where the least square approximation,

$$\log_{10}L\ (\text{km}) = 0.74M - 4.14$$

Table 1. Earthquake Faults in Japan Since 1891.

Date	Earthq.	M	Fault	L^{km}	Strike	Dh^{m*}	Dv^{m*}
1891 X 28	Nobi	7.9	Nukumi	20	N20–55W	3.0 L**	1.8 SW up**
			Neodani	35	N 0–40W	8.0 L	4.0 SW up
			Kurotsu	1	N17W	L	3.0 SW up
			Midori	1	N35W	4.0 L	6.0 NE up
			Daishogun	0.35	EW	—	5.0 S up
			Umehara	25	N70–80W	5.0 L	2.4 SW up
			Furuse	1			
			(total	80		8.0	6.0)
1894 X 22	Shonai	6.8		10	N50E?	—	—
1896 VIII 31	Rikuu	7.0	Senya	60	N20E	—	2.5 E up
			Kawafune	15	N20E	—	2.0 W up
1923 IX 1	Kanto	7.9	Sagami-B.	85	N45W	6.0 R**	3.0 NE up
			(many branch or secondary faults)				
1925 V 23	Tajima	6.5	Tai-East	—	N45E	—	— E up
			Tai-West	1.6	N45E	—	1.0 E up
1927 III 7	Tango	7.5	Gomura	18	N30W	2.8 L	0.75SW up
			(Takahashi, Nimbari, Nagaoka, Mie, Sugitani)				
			Yamada	7.5	N55E	0.8 R	0.7 NW up
1930 XI 26	Kita-Izu	7.0	Hakonemachi	2.5	N20E	0.3 L	0.5 E up
			Baragataira	0.5	N18W	0.5 L	0.2 W up?
			Tanna	7	N5 W	3.5 L	1.8 W Sc**
			Ukihashi-C.	4	N15E	3.0 L	2.4 W Sc
			Ukihashi-W.	4	N20E	2.0 L	0.5 E Sc
			Tawarano	1	N65W	0.4 R	— N up
			Oono	2.5	N30E	1.5 L	1.5 W Sc
			Kadono	2	N45E	2.0 L	0.6 E Sc
			Himenoyu	3	N70W	1.2 R	0.9 N up
			Harabo	—	NS	— L	— W up
			(total	30		3.5	2.4)
1943 IX 10	Tottori	7.4	Shikano	8	NS	1.5 R	1.0 S So.
			Yoshioka	4.5	NS	0.9 R	0.5 S up
1945 I 13	Mikawa	7.1	Fukozu	9	EW	2.0 L	2.0 S up
					NS	0.5 R	1.0 W up
			Yokosuka	16	EW	0.6 L	0.5 S up
					NS	—	1.2 W up
1948 VI 28	Fukui	7.3	sub-surface	25	N7–20W	2.3 L	0.7 E up
1974 V 9	Izu-Pen.	6.9	Irozaki	5.5	NW	0.45 R	0.2 SW up

* Dh and Dv denote horizontal and vertical displacements.

** L and R denote left and right-lateral slips. SW up, etc. show the sides upthrown, Sc the scissoring or hinge action.

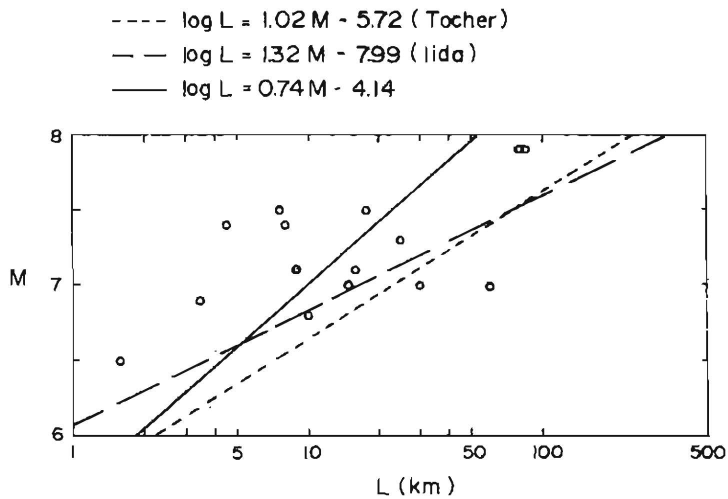

Fig. 19. Earthquake magnitude and the length of fault in the earthquakes given in Table I.

and corresponding lines by Tocher as well as by Iida are also indicated. The last expression is close to the formula proposed quite recently by Matsuda[30] giving L=80 km at M=8 and L=20 km at M=7;

$$\log_{10}L \text{ (km)} = 0.6M-2.9.$$

The equation by Tocher always gives larger values than ours and those by Iida are also too large in the greater magnitudes, which fact may seemingly be resulted from data in California, Alaska, Turkey, Mongolia, etc., thus suggesting that Japanese faults are likely shorter than those in the cited regions.

Plural faults, generally, were formed in an earthquake. The earthquakes in Table 1 excepting the Shonai earthquake are such cases. Moreover, descriptions on faults in the latter earthquake are not very reliable, as stated before. Thus, it must be expected that plural faults will be formed almost always in future earthquakes.

Bonilla[31] classified the earthquake faults into main, branch, and secondary faults, which have been employed in the preceding pages. The classification illustrated in Fig. 20. applies also to Japanese faults in many cases, but it seems not to be very appropriate for cases as the Rikuu, Tajima, Tango, Tottori, and probably the Mikawa earthquakes too, where two faults with dimensions of equal order were formed and it was impossible to judge which was the main. Also in other earthquakes the main fault was in general not a single connected rupture, but several segments en échelon appeared, forming an aggregated main fault system.

Accordingly, there are gaps or jumps between each segment fault, either longitudinally or laterally. Matsuda[5] refers to the "changing" from one segment to another in the Nobi and Kita-Izu earthquakes. The lateral gap is especially important in practice, because it implies the width of region calling for caution along a postulated fault. The distances experienced so far are 1.5 to 3 km in Nobi, 0.4 km

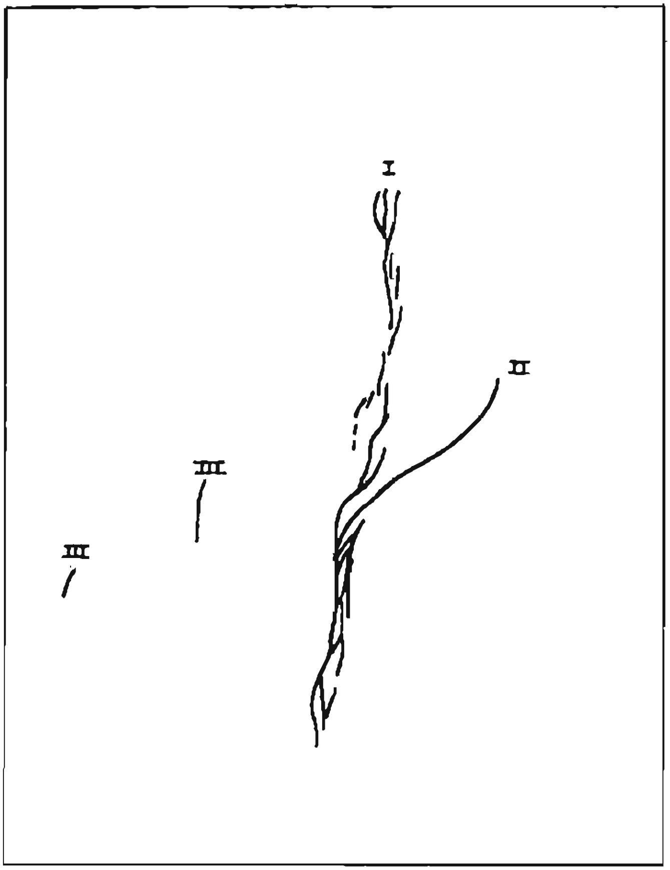

Fig. 20. Diagram showing (I) main fault zone, (II) branch fault, and (III) secondary faults. (rerpoduced from Bonilla)

in Tajima, 1 to 2 km in Kita-Izu, and 2 km in Tottori. About 12 km between the Kawafune fault and the Senya fault in the Rikuu earthquake is exceptionally high. The distances between the main fault and the secondary ones are comparable with or smaller than the above values, e.g. 1.5 km in Fukui, 0.25 to 0.5 km in the event off the Izu Peninsula etc. The Kanto earthquake is an exceptional case in which the secondary fault were distributed in an area as large as the dimension of the main fault.

As for the strike-slip fault it is well known that a pair of conjugate faults can arise with nearly perpendicular strikes to each other and that under a stress state there is a correlation between strikes and slip senses of each. For instance in the Tango Peninsula the Gomura fault with a strike N30°W is left lateral, while the Yamada fault of S55°W is right lateral. Similar cases are reported also in the Mikawa earthquake as well as in the Kita-Izu earthquake.

These displaced segments, composing an aggregated main fault system or a conjugated pair, can be considered to have been picked up from existing active faults so as to conform to the regional stress state. Therefore, it would not be quite correct if one would deduce the stress state from the orientation of the main rupture only, as is commonly done. Predicting a faulting pattern in a future, would become possible if determining the characteristics of each active fault as well as the regional stress state would be realized with sufficient reliability.

The maximum displacement, either horizontal or vertical, on the main fault is given by Iida[29] for data from the whole world as

$$\log_{10}D = 0.55M - 3.71$$

Bonilla[31] investigated into historic surface faults in the United States and Mexico and derived

$$\log_{10}D = 0.57M - 3.91\ .$$

Matsuda[30] presented the following relation for on-land earthquakes in Japan

$$\log_{10}D = 0.6M - 4.0\ .$$

In hazard assessment the significance of horizontal and vertical displacements are different, and the amounts in the horizontal and vertical directions in Table 1 are plotted separatedly in Fig. 21 and 22. Empirical equations by the method of least square are

$$\log_{10}D_h(m) = 0.78M - 5.36$$

and

$$\log_{10}D_v(m) = 0.44M - 3.07$$

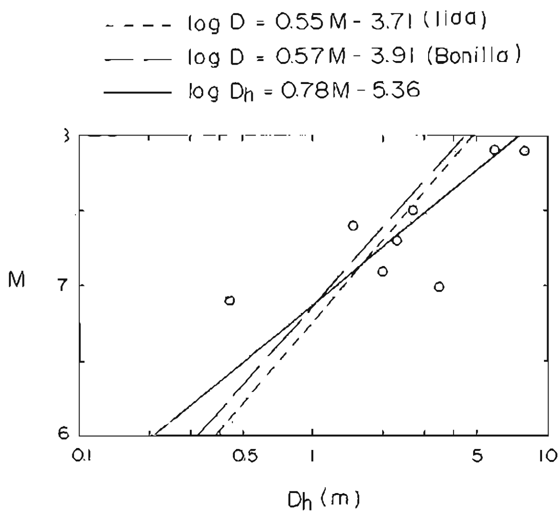

Fig. 21. Earthquake magnitude and the maximum horizontal displacement on fault in the earthquakes given in Table 1.

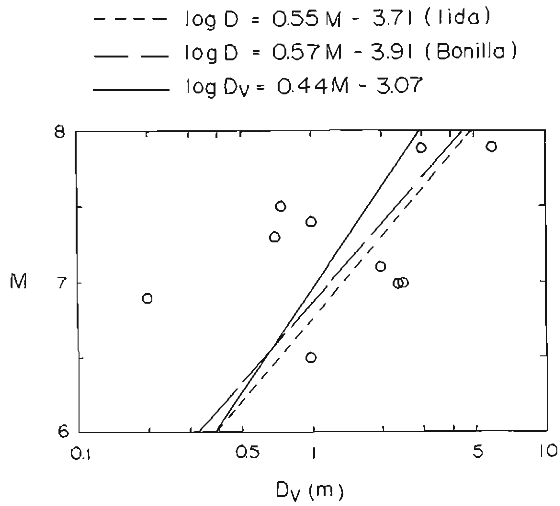

Fig. 22. Earthquake magnitude and the maximum vertical displacement on fault in the earthquakes given in Table 1.

for the horizontal and vertical displacements, respectively. The relations by Iida as well as by Bonilla are also given in the figures.

From Table 1 or Fig. 21 and 22 it is noted that the horizontal displacement is predominant in Japanese faults. The cases $D_h > D_v$ are the Nobi, Kanto, Tango, Kita-Izu, Tottori, Fukui and the off Izu-Peninsula earthquakes, while the cases $D_h < D_v$ are the Shonai, Rikuu, Tajima, and Mikawa earthquakes. In the latter group the result on the Shonai event is unreliable, and moreover also in the Rikuu earthquake, where only the value of D_v is reported, it is not very certain that there was no horizontal displacement, since the horizontal shift is more difficult to determine than the vertical one without detailed survey.

The sense of vertical slips is in general not so simple or systematic as that of horizontal ones. In some cases one side of a fault is elevated consistently along its whole length, while in others the side uplifted is opposite at the both ends of a fault resulting in a so-called hinge fault. The hinge action was observed at the Tanna and other faults in the Kita-Izu earthquake as well as at the Shikano fault in the Tottori earthquake. It is interesting to note that the SW side was uplifted in the main part of the Nobi-main fault, while the NE side was uplifted in the concealed fault in the Fukui plain, which is supposed to be an extension of the former. The both faults may be seen to form a hinge fault in a macroscopic scale.

In assessing the direct hazard from faulting, the width of fault rupture is an important parameter. According to Steinbrugge[4] the width of an actual fault break may be very narrow, and the 1906-San Francisco faulting had the appearance of a furrow turned by a plow. In contrast to this the widths of fault ruptures reported in Japan are mostly rather large regardless of their morphology as mole tracks, grabens, or en échelon fissures. For instance the mole tracks in the Mikawa earthquake exhibited widths of 40 to 60 m, the grabens in the Tajima event measured 30 m, and the belt of en échelon fissurring along the Gomura fault in Tango were 5 to 20 m and those in the Izu Peninsula, 5 to 10 m.

In fact the fault zone may be narrower for strike-slip fault than they are for normal or reverse faults. However, even traces of strike-slip fault cannot remain narrow but form en échelon fissuring belt when the ground surface is covered by weak deposits.

6. Conclusions

Well-known earthquake faults since 1891, when the greatest on-land earthquake in Japan occured, are summarized; specifically those formed in the Nobi, Shonai, Rikuu, Kanto, Tajima, Tango, Kita-Izu, Tottori, Mikawa, Fukui, and off Izu-Peninsula earthquakes. On the basis of experiences in these cases morphology of hazards from faulting, distribution of damage, dimensions of faulting as well as the region at risk around active faults are discussed.

Types of hazards from faulting are horizontal as well as vertical offsets across faults and various types of rupture or deformation of ground such as grabens, mole tracks, tension cracks en échelon, gentle flexure or wavy swelling on the ground surface, etc.

According to data in earthquakes accompanied by surface faulting the distributions of equal percentages of collapsed houses or seismic intensities are not concentric but rahter oval, surrounding the line of surface break.

The percentage of totally collapsed houses is a function of the distance of a site from the surface fault, and according to results in the Tango, Kitaizu, and Fukui earthquakes of M 7.0 to 7.5, the width at risk being exceeded by 30 % of totally collapsed houses would be 5.5 to 7.5 km in mountainous regions and some ten kilometers in alluvial plains.

The lengths of faulting in on-land earthquakes occurring since 1891 in Japan, plus the Kanto quake may be approximated as follows,

$$\log_{10} L\ (\mathrm{km}) = 0.74M - 4.14\ .$$

The result suggests that Japanse faults are likely shorter than those in North America and other parts of the world.

Another fact characteristic in faulting in Japan is that two faults with dimensions of equal order which can hardly be judged as the main or secondary are formed with a relatively high frequency. Main faults also are in general not a single connected rupture, but composed of several segments in échelon arrangement.

Accordingly, there are gaps between ends of each segment forming main faults, and the values of lateral gaps experienced are 0.4 to 3 km. The 12 km of the Rikuu earthquake is exceptionally high. The distances between the main fault and the secondary are 0.25 — 1.5 km.

The maximum horizontal as well as vertical displacements across faults are

$$\log_{10}D_h = 0.78M - 5.36$$

and

$$\log_{10}D_v = 0.44M - 3.07$$

It can be stated that horizontal displacement is predominant in most earthquake faults in Japan.

The widths of fault ruptures in Japan are mostly rather large regardless of their morphology, and have attained values of 40 to 60 m as mole tracks, 30 m as grabens, 5 to 20 m as en échelon fissurring.

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