EARTHQUAKE DAMAGE, DAMAGE PREDICTION AND COUNTERMEASURES IN TOKYO

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I. INTRODUCTION

The Kanto Plain has often been subjected to destructive earthquakes. Kawasumi (1970) studied earthquakes with intensity of 5 or more in JMA (Japan Meteorological Agency) Scale in Kamakura City, Kanagawa Prefecture, as reported in ancient documents. Intensity of 5 in JMA Scale is nearly equal to that of 8 in Modified Mercalli's one. As a result, he detected the periodicity in the reccurrence of destructive earthquakes and theorized that major earthquakes with intensity 5 or more would repeatedly shocked Kamakura City every 69 years with a possible aberration of plus and minus 13 years. Also, he noticed that Tokyo stands in same situation. According to Kawasumi's treatise, we have entered into the epoch of imminence since 1978. By the way, the last destructive earthquake to hit Tokyo was the Great Kanto Earthquake of 1923.

Usami (1976) analysed the earthquakes which shocked Tokyo at intensity of 5 or more in JMA Scale since 1600. As a result, he noticed that Tokyo has been affected by such earthquakes ten times a century.

We can say, at least on the basis of these theories, that areas in Tokyo which have not experienced an earthquake with intensity of 5 or more since 1929 may now have a greater probability than ever of being hit by another major earthquake.

II. RECORDS OF EARTHQUAKES IN TOKYO

Usami (1976) has shown that there were a total of 37 earthquakes with intensity of 5 or more in JMA Scale in Tokyo since 1600. They are listed in Table 1 and their epicenters are indicated in Fig. 1.

The damage was especially extensive in the Ansei Earthquake of 1855 and the Great Kanto Earthquake of 1923 because of the fires that followed them. But a distinction is made between the two earthquakes; the destruction of houses was due more to the direct impact of ground motion than to fires in the case of 1855 earthquake and on the other hand, fires were the chief cause of the destruction in 1923.

There were also three other earthquakes of smaller scale in terms of damage, these occurring in 1649, 1703 (the Genroku Earthquake) and 1894. It is believed that scores of persons were killed in each of the earthquakes. Earthquake of lesser intensity also caused destruction, deaths and injuries when their foci were near Tokyo.

Major earthquakes usually originate in and around the transform fault along the eastern

Table 1 Earthquakes that have damaged Tokyo (Compiled from the data after Usami, T., 1976)

Data of occurrence	Focus		Magnitude	Intensity in Tokyo	Degree of damage in Tokyo	Damage in Tokyo
	Longitude (E)	Latitude (N)				
June 26, 1615	139.7	35.7	6.4	6	3	Many houses collapsed, many people killed and injured. Ground cracked.
Aug. 10, 1628	–	–	6.1	5	1	Stone walls of Edo Castle crumbled.
Aug. 2, 1630	–	–	6.7	5	1	Stone walls of Edo Castle crumbled.
Mar. 1, 1633	139.2	35.2	7.1	5	0	
Mar. 12, 1935	–	–	6.1	5	1	Walls of some houses collapsed. Most of stone lanterns at Zojoji Temple fell.
Dec. 6, 1643	–	–	6.2	5	1	Roofs and walls of houses gave way.
June 16, 1647	–	–	6.4	5	2	Stone walls and gates of Edo Castle collapsed. Many houses collapsed and quite a few died.
Sep. 9, 1647	–	–	–	5	1	Stone walls of Edo Castle crumbled.
June 12, 1648	139.2	35.2	7.1	5	1	Roof tiles of many houses fell.
July 30, 1649	139.8	35.7	7.1	6	2	Stone walls of Edo Castle were damaged. Many houses collapsed and many were crushed to death under collapsed houses.
Sep. 1, 1649	139.7	35.5	6.4	5	1	Some structures in Edo Castle were damaged.
June 18, 1683	139.7	36.8	7.3	5	1	
Nov. 25, 1697	139.6	35.5	6.9	5	1	Stone walls of Edo Castle crumbled.
Dec. 31, 1703	139.8	34.7	8.2	6	3	Many houses collapsed and fires broke out. Many were killed. Tsunami hit the southern coast.
Oct. 21, 1706	139.8	35.6	6.6	5	1	Stone walls of Edo Castle were damaged.
Oct. 28, 1707	135.9	33.2	8.4	5	0	
May 14, 1746	–	–	6.9	5	1	Some houses were damaged.
Aug. 23, 1782	139.2	35.2	7.3	5	2	Some houses collapsed. Some died.
Aug. 29, 1784	139.8	35.6	6.1	5	1	Many houses tilted and roof tiles of them fell.
Dec. 7, 1812	139.7	35.5	6.6	5	1	Many houses collapsed.
Dec. 23, 1854	137.8	34.0	8.4	5	1	Some houses were damaged.
Nov. 11, 1855	139.8	35.6	6.9	6	4	More than 10,000 people killed. Houses collapsed and burned reached about 20,000.
Nov. 4, 1856	–	–	6.6	5	1	
Feb. 22, 1880	139.8	35.4	5.4	5	1	
Oct. 15, 1884	139.8	35.7	–	5	1	Brick walls of houses were cracked.
Feb. 18, 1889	139.7	35.4	5.7	5	1	
June 3, 1892	139.8	35.7	6.2	5	1	Twenty-nine houses were broken.
June 20, 1894	139.8	35.7	7.0	6	3	Twenty-four people were killed and 157 injured. Ninety houses collapsed and about 5,000 were partly broken.
Oct. 7, 1894	–	–	7.0	5	2	Roof tiles and walls of many houses were damaged.
Jan. 18, 1895	140.3	36.2	6.8	5	2	A man were killed and 31 people were injured.
Feb. 24, 1906	139.8	35.5	6.7	5	2	Roof tiles and walls of many houses were damaged.
Apr. 26, 1922	139.4	35.1	6.4	5	2	Walls of 82 houses fell.
Sep. 1, 1923	139.3	35.2	7.9	6	4	Ref. Table 2.
Jan. 15, 1924	139.2	35.5	6.7	5	2	Sex people were killed and 116 were injured. One hundred and three houses were collapsed and 1,692 were partly damaged.
Aug. 3, 1926	139.5	35.3	6.2	5	1	Gas pipes were broken.
July 17, 1929	139.1	35.5	6.1	5	1	Telephone lines and water pipes were broken. Three fires broke out.

Degree of damage: 0: No damage.
1: Slight damage; Houses did not collapsed but were broken.
2: Light damage; Many houses were damaged but few of them collapsed.
3: Medium damage; Considerable number of houses collapsed, Some people killed and many were injured.
4: Serious damage; Catastrophic damage was caused.

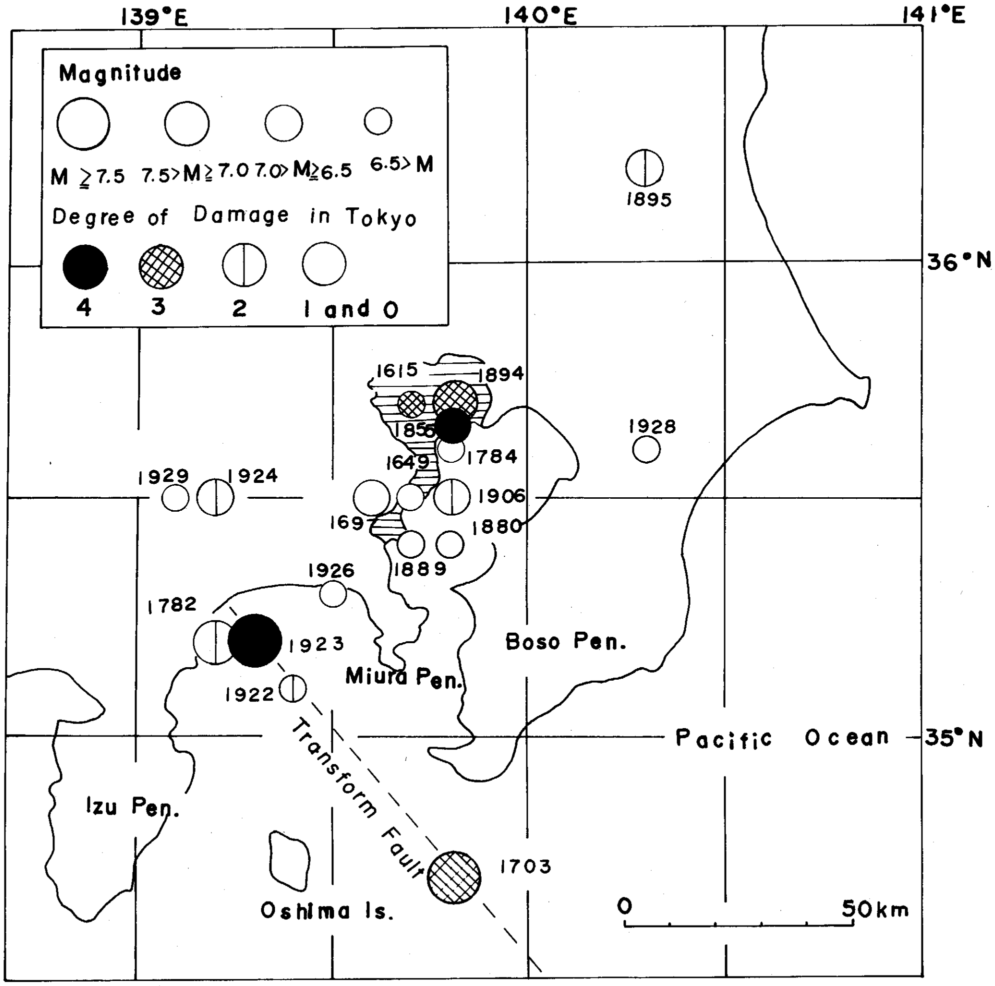

Fig. 1 Foci and magnitude of earthquakes that have damaged Tokyo since 1600. Degrees of damage in Tokyo are same as those on Table 1.

edge of the Sagami Trough which stretches from Sagami Bay to waters south of the Boso Peninsula (Fig. 1). The magnitude of the Genroku Earthquake of 1703 was 8.2 on the Richter's Scale and that of the Great Kanto Earthquake was 7.9. It is said that another catastrophic earthquake having intensity and a focus similar to those of the Great Kanto Earthquake occurred in 818. Earthquakes focused in or near the area as the Great Kanto Earthquake also shook Japan in 1241 (magnitude of 7.0 on the Richter's Scale), 1433 (7.1), 1648 (7.1) (Usami, 1975).

Both of the Ansei Earthquake and the earthquake of 1894 had magnitudes of 6.9 and 7.0 respectively, which, compared with the Great Kanto Earthquake and the Genroku Earthquake, were less intensive. Nonetheless, they inflicted devastating damage on Tokyo because their foci were directly under the metropolis. Such earthquakes are called "direct-hit type earthquake" and were also recorded in 1615 (6.4), 1649 (7.1 and 6.4) and

1812 (6.6). In the 1894 earthquake, only 0.5 percent of wooden houses were destroyed while the rate was as much as 10 percent with brick buildings which were introduced to Japan with the turn of the Meiji Period.

III. DAMAGE BY THE GREAT KANTO EARTHQUAKE

The extent of the damage was examined on the basis of the reports made by the Imperial Earthquake Investigation Committee (1925 a, b)

1. Outlines of the Earthquake

Time of occurrence was 58 minutes and 32 seconds past 11 a.m., September 1, 1923. The focus was originally estimated to be at 139.3°E and 35.2°N and the magnitude at 7.9. But Kanamori and Miyamura (1970) placed its focus at 139.2°E and 34.5°N (plus and minus 15 km) and estimated its depth to be from 0 to 10 km and the magnitude at an average of 8.12. The earthquake resulted from a slippage of transform fault between two crustal blocks bounded by the Sagami Trough (Kanamori and Ando, 1973).

The damage was the severest in the Kanagawa and Tokyo Prefectures. It also extended to other parts of the Kanto Region, Shizuoka Prefecture and such remote prefectures as Yamanashi and Nagano (Table 2). The number of deaths in the Kanagawa and Tokyo Prefectures was totalled about 97,000 including about 60,000 in Tokyo City. While the total number of dead and missing reached about 143,000, about 104,000 people were listed as injured.

About 128,000 structures were demolished, other 126,000 were heavily damaged and as many as 447,000 structures were lost in fires. Fires were responsible for the loss of homes in almost all cases in Tokyo while about 50 percent of houses destroyed in Kanagawa Prefecture were attributed to fires.

Table 2 Damage caused by the Great Kanto Earthquake of 1923.
(after Imperial Earthquake Investigation Committee, 1925a)

Prefecture	Life			House				
	Died	Injured	Missing	Totally collapsed	Half collapsed	Destroyed by fire	Washed away by tsunami	Total (excluding half-collapsed)
Tokyo (Tokyo City)	68,215 (59,065)	42,135 (15,674)	39,304 (1,055)	20,179 (3,886)	34,632 (4,230)	377,907 (366,262)		398,086 (370,148)
Kanagawa (Yokohama City) (Yokosuka City)	29,065 (23,440) (540)	56,269 (42,053) (982)	4,002 (3,183) (125)	62,887 (11,615) (8,300)	52,863 (7,992) (2,500)	68,569 (58,981) (3,500)	136	131,592 (70,496) (11,800)
Chiba	1,335	3,426	7	31,186	14,919	647	71	31,904
Saitama	316	497	95	9,268	7,577			9,268
Yamanashi	20	116		1,763	4,994			1,763
Shizuoka	375	1,243	68	2,298	10,219	5	661	2,964
Ibaraki	5	40		517	681			517
Nagano				45	176			45
Tochigi		3		16	2			16
Gunma		4		107	170			107
Total	99,331	103,733	43,476	128,266	126,233	447,128	868	576,262

The earthquake stirred up huge waves of tsunami which washed away 868 houses in the three Prefectures of Shizuoka, Kanagawa and Chiba.

It was also accompanied by violent crustal movements. As a result, the maximum amount of upheaval was recorded two meters at the southern tip of the Boso Peninsula and the coastal area of Sagami Bay. The upheaval at the tip of the Miura Peninsula measured 1.2 meters. But the inland area near Mt. Tanzawa of Kanagawa Prefecture sank a maximum of 1.6 meters.

Records show that tsunami of three meters high pounded the southern coast of the Izu Peninsula and that it was four or six meters high at the coast of Sagami Bay and the southern coast of the Boso Peninsula. The damage by tsunami was most conspicuous on the lowlands along small bays such as Atami of Sizuoka Prefecture and Ainohama on the tip of the Boso Peninsula. Tokyo Bay was only washed by waves of less than one meter high.

2. Damage by fire in Tokyo

The Great Kanto Earthquake claimed a historic number of deaths and damage because of fires. Fires broke out at about noon of September 1 and continued to rage for 40 hours till 4 a.m., September 3 scorching 44 percent of the City of Tokyo. About 370,000 houses were lost in the fires. In the aftermath of the fires, police counted about 60,000 people either dead or missing, the figure representing 2.5 percent of the City's population which then stood at 2,437,000.

The hardest hit was Honjo-ku (ward) (southwestern half of today's Sumida-ku) where one out of every six persons was killed. The fires were to blame for 98 percent of destroyed houses and 85 percent of those dead and missing.

In all of Tokyo 183 fires broke out and 127 of them spread to neighbouring buildings. Eighty-eight of the fires originated at cooking ranges, hibachi (fire-box) and charcoal stoves at homes and eating houses. Twenty-seven fires were caused by chemicals and explosives. As many as 52 fires were set by flying sparks. It is well imaginable that fires started almost simultaneously and evolved into huge conflagrations beyond control. In examining the sources of the fires, it was found that 35 fires started in private homes, 26 in processed food maker's establishments and other 15 fires in eating houses. Eighteen fires which broke out in schools and laboratories were triggered by chemical products.

Tornadoes with varying force were caused by the fires. Large and strong tornadoes uprooted or broke trees measuring 40 to 50 centimeters in diameter and tossed people, carriages and the roofs of buildings skyward. It is said that most of the tornadoes rotated in an anticyclonic fashion. Tornadoes were mostly created in an area encircled by fires which had spread to the area in two or three directions. The most serious destruction was caused by tornadoes in a site formerly occupied by a clothing depot. In Honjo-ku being located in the east of the River Sumidagawa, the fires started immediately after the earthquake spread in a northwesterly or northerly direction on south-southeast winds.

Two or three hours after the fires started, they had burned the entire western section of Honjo-ku except the former site of a clothing depot. Tens of thousands of people had fled to the huge vacant lot covering 66,000 square meters and tornadoes struck there at about 3:30 p.m.. They blew bricks, timbers, carts and every other thing sky-high. Then, an ascending current was created and sent aloft human beings with carts carring properties of the evacuees. After that, sparks of fire showered on the plot and on the paraphernalia the people had fled with and the fires turned the place into an inferno. The flames were brought undercontrol at about 6 p.m.. But the fire which lasted only one or two hours burned to death or suffocated a total of 35,000 persons.

The Ansei Earthquake caused just as wide destruction through fires. It is said that fire broke out at 50 places and 45 fires spread out. The heaviest damage was dealt to Shin-yoshihara (today's Taito-ku) where the earthquake hit as a fire started one hour earlier was still raging. It was made even more disastrous because the ground conditions were particularly bad.

IV. PREDICTION OF EARTHQUAKE DAMAGES

1. Tokyo Earthquake and Fire Prevention Ordinance

As reviewed in the previous section, Tokyo is prone to danger to life and property from earthquakes. Planning countermeasures for earthquake damage is one of the urgent administrative problems for Tokyo Metropolitan Government.

It is indispensable for reduction of earthquake damage to adopt comprehensive countermeasures including not only earthquake-resistant construction but also land-use management etc. (White and Haas, 1975). Tokyo, however, has been so crowded that it is too late to adopt such countermeasures as land-use management or building regulation. Countermeasures based on the regional difference between predicted earthquake damages or the peculiarities for disaster is more rational on the case of such overcrowded city as Tokyo.

The Tokyo Metropolitan Assembly legislated the Tokyo Earthquake and Fire Prevention Ordinance in 1971. The ordinance makes it compulsory for Tokyo Metropolitan Government to survey the degree of danger according to the regional characteristics and to announce the results of such surveys.

The primary objectives of the surveys are as follows (Tokyo Metropolitan Government, 1976):

(1) To make the results of the surveys a guideline in the materialization of a city where damage from earthquake disasters could be kept to minimum;

(2) To further the awareness of the citizens of Tokyo regarding earthquakes and make them more conscious of ways and means to keep damage from the disaster to the minimum;

(3) To make the survey a guidepost in selecting areas where the implementation of earthquake and fire countermeasures should be given priority.

2. Survey on damage potential according to regional characteristics

To answer the question that citizens in what area of the city will be exposed to the most danger from fires and falling buildings in times of a hazardous earthquake, Tokyo Metropolitan Government carried out relative damage potential survey.

Before carrying out the survey, the survey area (the twenty-three wards in the City) was divided into approximately 2,300 blocks, each measuring 500 meters square. Various elements relevant to earthquake damages in each block were subjected to five grades of relative evaluation based on an aptitude to suffer damages. These elements and the procedure of the survey are shown on Fig. 2.

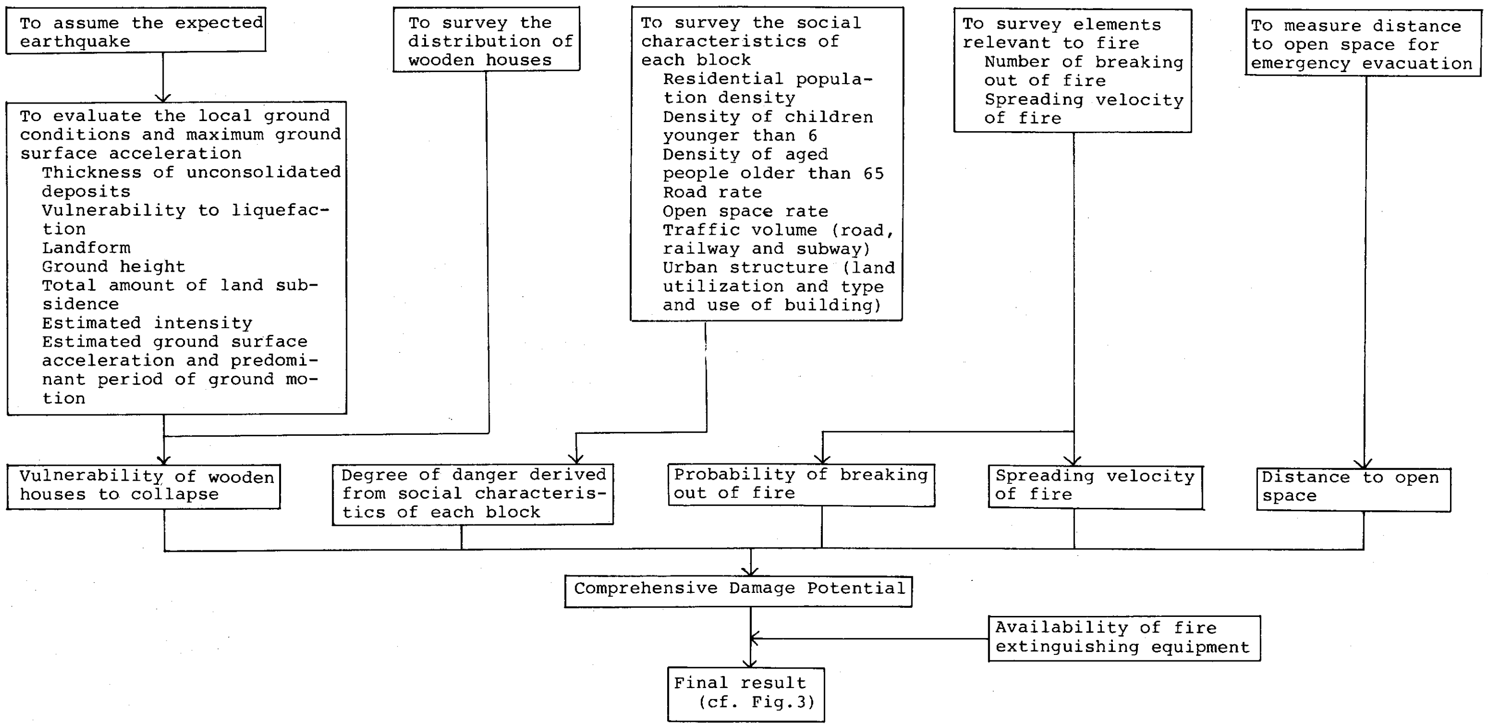

Fig. 2 Flow diagram of survey on damage potential.

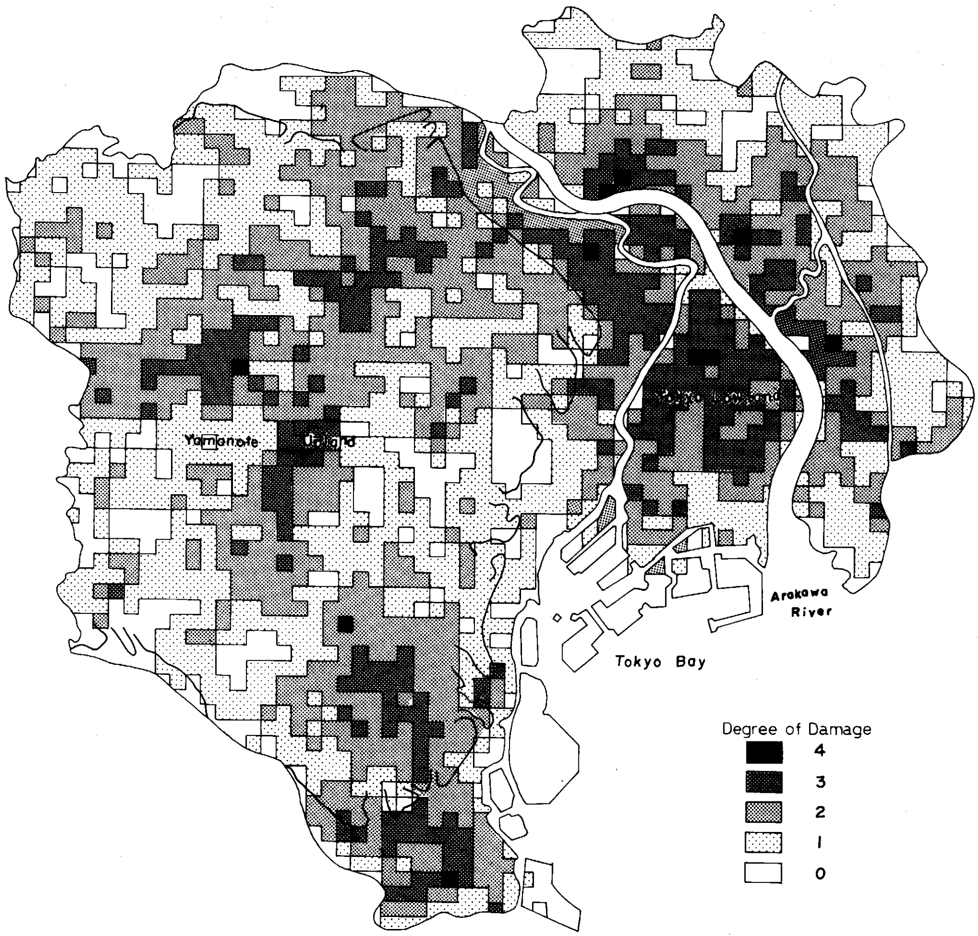

Fig. 3 Final results of the survey on damage potential.

The following six basic works were carried out as a first step:

(1) To assume the expected earthquake;
Supposing that an earthquake with the magnitude of 7.9 and an epicenter in Sagami Bay (same as those of the Great Kanto Earthquake of 1923) would occur in an evening in midwinter, the survey was carried out.

(2) To evaluate local ground conditions and maximum ground surface acceleration caused by the earthquake;
Scrutinizing many boring logs, superficial geological conditions were analysed. On the basis of the results, response analyses were carried out. Adding these works, other elements or characteristics representing local ground conditions such as ground height and an aptitude to cause liquefaction were surveyed. The physical conditions of each block were evaluated in this procedure.

(3) To survey the distribution of wooden houses;
Wooden houses were classified by the date of building and their numbers within each

block were counted.

(4) To survey the social characteristics of each block;
The peculiarities of each block were regarded to result from seven elements listed in Fig. 2. Meshworks were done for these elements respectively. The works of (3) and (4) survey some social conditions being concerned in earthquake damage.

(5) To survey elements relevant to fire;
As mentioned in the previous chapter, fires caused soon after an earthquake are apt to become the most destructive source of disaster. Extension of damage deduced from them may be a function of the number of their breaking out and their spreading velocity. The elements relevant to these matters were surveyed.

(6) To measure distance to open spaces for emergency evacuation;
Distance to open spaces for emergency evacuation is one of the important factors acting on increase or decrease in casualities in times of fire. Distance from each block to the nearest open space was measured.

Using the results of the first step works, the five kind of damage potential were calculated for each block. Five grades of 0 to 4 were given to each block on the basis of the results of the calculation. The five kinds of potential were as follows:

(1) Vulnerability of wooden houses to collapse;
This vulnerability was deduced from combining the results of the works of (2) and (3) in the first step.

(2) Degree of danger derived from characteristics of each block;
Ranks of seven elements were added at every block.

(3) Probability of breaking out of fires;
Adopting statistical method, the probable number of breaking out of fire were calculated on the basis of the data obtained from the work of (5) in the first step.

(4) Spreading velocity of fire;
The equation obtained by Hamada et al (1973) was used. They noticed that the spreading velocity of fire is a function of building-to-land rate, ratio of area occupied by wooden houses to that by all structures and wind velocity.

(5) Distance to open spaces for emergency evacuation.

After the grades of the five kinds of damage potential were added up at every block, the availability of fire extinguishing equipment in each block was placed under consideration. If a fire comencing to spread could be extinguished, there should be a substantial decrease in damage.

The final rankings are shown in Fig. 3. Grade 4 means that the block has the highest damage potential. It must be mentioned that these grades do not give the extent of damage but the relative degree of danger by putting the physical and social conditions together.

Tokyo Metropolitan Government carried out the survey in 1978 for the purpose of quantitatively estimating earthquake damage. The survey procedure is shown in Fig. 4. Dimension and a focus of the expected earthquake are assumed same as those used in the relative damage potential survey mentioned previously. Adding them, three other conditions were assumed: it would not have rained for several days before occurrence of the earthquake, wind would be blowing from NNW with velocity of 6 meters per second and it would be high tide level in Tokyo Bay, when the earthquake would shock Tokyo.

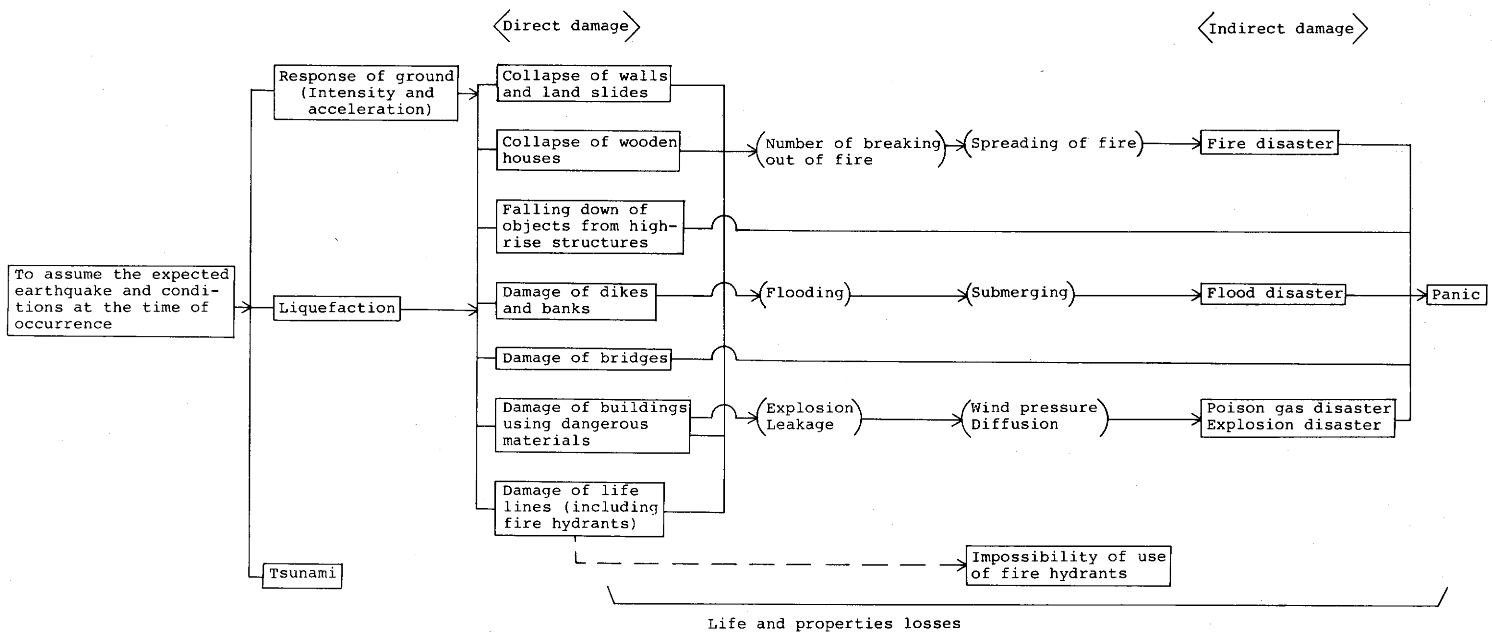

Fig. 4 Flow diagram of survey on quantitative estimation of earthquake damages.

Table 3 Calculated damage of the expected earthquake.

Totally Collapsed Wooden Houses	62,000
Collapsed Walls and Landslips	1,300
Damage of Major Bridges	3
Damage of Water Supply Pipes (main pipes only)	220
Damage of City Gas Pipes	670
Houses burned by Fires	470,000
Houses Suffering from Floods	11,000
Sufferers	3,500,000
Affected Families	1,200,000
Injured	63,000
Died	36,000

The survey took two stages of damage into consideration. The first stage is the direct damage due to ground vibration and liquefaction. Tsunami supposed not to be serious in this survey. The second stage is the indirect damage such as fire, floods *etc*., which will be triggered by the direct damage.

The results of the survey are listed in Table 3. Including 470,000 which were supposed to burn by fires, the number of ruined houses ran up to 543,000. Though 63,000 among 3,500,000 sufferers were presumed to die, it may be said that the number of deaths were underestimated. Taking account of occurrence of such the catastrophe as seen in the site formerly occupied by a clothing depot in 1923, the number of deaths should become much greater.

The authors would like to mention that these two surveys were carried out by many kinds of specialists such as technologists majoring in seismic engineering, civil engineering, urban planning and system engineering, psychologists, geographers etc. Among them, Nakano, T., one of the authors, supervised the team.

V. COUNTERMEASURES FOR EARTHQUAKE DAMAGE

There are two kinds of countermeasure for earthquake damage. One is the so-called hard countermeasure and the other is soft. The hard countermeasure means structural protection such as construction of earthquake- and fire-resistant buildings, redevelopment of a built up area, laying down water tanks for fire fighting etc. On the other hand, land use management, establishment of relief system, planning the way how to evacuate from fires, adoption earthquake insurance etc. are regarded as the soft countermeasures.

The main countermeasure projected by Tokyo Metropolitan Government is for fires which may occur simultaneously in many independent sites. Accordingly the countermeasure includes designation of open spaces for emergency evacuation, construction of fire-resistant highrise buildings, laying down water tanks along the roads to the open spaces in order to ensure evacuation routes, construction of open spaces to be used for disaster prevention etc.

Originally, 46 open spaces were designated by the Disaster Prevention Council, Tokyo Metropolitan Government, for emergency evacuation. The reason why these spaces were chosen is that they have open spaces more than 300 meters away from crowded wooden houses prone to burn. But some of them require people to take more than 10 kilometers of walking to reach. Accordingly, other 75 spaces were newly added to them and a total of 121 spaces have been designated for emergency evacuation. They are usually used for parks, green tracts, university campuses, residential areas being composed of reinforced concrete buildings, dry river beds etc.

Construction of open spaces was planned together with redevelopment of a built up area especially in Koto area. The Koto area is located in the deltaic lowland and was most severely damaged by the Great Kanto Earthquake. Almost all the area was burned as well as severely damaged by ground motion, because the thickness of very soft clayey deposits reaches more than 30 meters (Kaizuka, Naruse and Matsuda, 1977) and wooden houses were crowded there.

Construction of open spaces was planned in five sites in the Koto area. While one of them has been completed, no start has yet been made with the work for the rest. The open space constructed in Shirahige, northern part of the Koto area is surrounded by fire-resistant highrise buildings designed to shelter the area from fires and is usually used as a public park and an athletics ground.

The Tokyo Metropolitan Government paid some 500,000 million yen, about one third of its annual budget, for construction of the open space. This extremely high cost is preventing the construction of other open spaces.

VI. A COMMENTARY ON PRESENT DAY TOKYO

Tokyo is much different from what it was at the times of the Great Kanto Earthquake. The urban area has vastly expanded while the density of wooden houses has rapidly increased. As the number of people commuting to work in Tokyo has multiplied, terminal stations are normally filled with commuters during rush hours.

As mentioned previously, the cause of catastrophe deduced by the Great Kanto Earthquake was triggered by the fires which broke simultaneously in many sites. Today, a great variety of buildings using fire all the time are scattered throughout Tokyo. Most homes use kerosene stoves in winter. In times of the Tokachi-Oki Earthquake of 1968, 1.32 percent of the total number of kerosene stoves became the origins of fires in Towada City.

Under these circumstances, it is clear that a major earthquake will set off fires in many parts of the city regardless of the time of day that it might occur. In the last great earthquake, people were burned to death or died through inhalation of smoke. In addition to these causes of fatalities, there now are huge volumes of chemical products which, when burned, will emit gases that will poison people to death.

Today, we see many more places that may trap and kill people in an earthquake than 57 years ago, such as the ever-expanding networks of subways, underground shopping complexes and a sharply increasing number of multi-purpose buildings. Destruction of dikes will cause floods in the deltaic lowland where land subsidence has been progressing due to excessive withdrawal of ground water (Nakano and Matsuda, 1976). The area of land below sea level in Tokyo is about 68 square kilometers. Also, the dikes which had been built to prevent floods has been weak after repeated attempts to raise their heights. In deltaic lowlands, a catastrophic damage will be brought about by floods even if fires could be prevented.

The Japanese people are now totally dependent on the supply of tap water, city gas and electricity in their daily life. Having no access any longer to alternative sources such as wells and charcoal stoves, they will be helpless when these services are stopped all of a sudden. Damage of these life lines occurred in Sendai City during the Miyagi-ken Oki Earthquake of 1978 and was called an urban type damage.

It can be said that the specter of such a calamity mentioned in this paper is approaching us definitely. There is every reason to step up preparations against coming major earthquake.

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