Comprehensive Urban Studies No. 44 1991

Seismic Intensity in 1989 Loma Prieta Earthquake

Norio Abeki[1) Takahisa Enomoto[2)
Hitomi Murakami[3) Toshio Mochizuki[4)

1. INTRODUCTION

The October 17th, 1989 Loma Prieta earthquake occurred about 110 km southeast of San Francisco. The epicenter was above the San Andreas Fault. Not only the epicentric area was damaged. The earthquake damaged a wide range of area, extending as far as 100 km north to the metropolitan areas of San Francisco and Oakland. Residents along the coastal landfill areas suffered severe damage. The San Francisco-Oakland Bay Bridge and a major freeway overpass partially collapsed. The lifeline system was disrupted and drastically affected many citizens' lives in the greater metropolitan area. The earthquake motion was recorded by the USGS and CDMG, which obtained extensive observations and measurements of earthquake motion and damage at various locations. Near the epicentric area the horizontal components Max. Acceleration indicated a large reading of 0.64g Corralitos, 0.54g in Capitola. The vertical component indicated a reading of 0.5 to 0.6g. The neighboring Oakland area showed 0.26g in Emeryville. At the Golden Gate Bride in San Francisco a reading of 0.24g was reported; and 0.33g at the San Francisco International Airport. The seismic intensity distribution was reported by USGS. According to the USGS report, the Modified Mercalli Seismic Intensity Scale was 8 (the JMA scale 5 to 6) at the epicentric area. Though the MM scale 7 (JMA scale 5) was recorded in San Francisco and Oakland, one particular section of these two cities showed MM 9 (JMA 6 to 7). This area experienced considerable damage. The USGS is using microzoning maps of the San Francisco Bay Area based on the intensity distribution survey questionnaire. USGS has examined this material in order to understand the correspondence between the microzoning map, which is based on a study of the classification of ground condition, and seismic intensity.

USGS has completed the seismic zoning map pertaining to the San Andreas Fault which runs through many areas of earthquke prone California; and, the Hayward Fault which runs trough the San Francisco Bay Area where a major earthquake is predicted. The zoning map is for prediction of the intensity distribution of the next large earthquake. This is based on the 1906 earthquake damage, seismic fault, and geological features, and ground condition. The Loma Prieta's disaster area coincides with the previous seismic intensity predictions. The research result will make a significant contribution toward future earthquake engineering and prevention of earthquake disaster.

1) Kanto Gakuin Univ. 2) Kanagawa Univ. 3) Hokkaido Univ. 4) Tokyo Metropolitan Univ.

2. The distribution of seismic intensity in the Bay Area

2. 1. The distibution of seismic intensity

Understanding the intensity of shaking and the characteristics of the ground vibration at the time of an earthquake is extremely important and generally of basic interest for understanding and reducing the impact of an earthquake disaster. Fig. 1 shows the intensity distribution in the San Francisco Bay Area during the Loma Prieta earthquake according to the USGS Modified Mercalli (MM) intensity scale. In Fig.1, the evaluation of intensity is based on data obtained from observation of stroung earthquakes and from surveys of quake-stricken areas, but the information on the more extended area is based on direct responses wired to the National Earthquake Information Center by post offices, and police and fire departments after every relatively big earthquake.

The MM scale is divided into 12 levels of shaking from I to XII (Table 1). Fig. 1 shows the distribution of intensity level VIII of the MM scale for areas near the hypocenter such as Los Gatos and Watsonville, and level VII for the larger area along the Pacific Coast from Salinas south of th hypocenter to northern Berkeley. In some parts of San Francisco and Oakland we find high intensity.

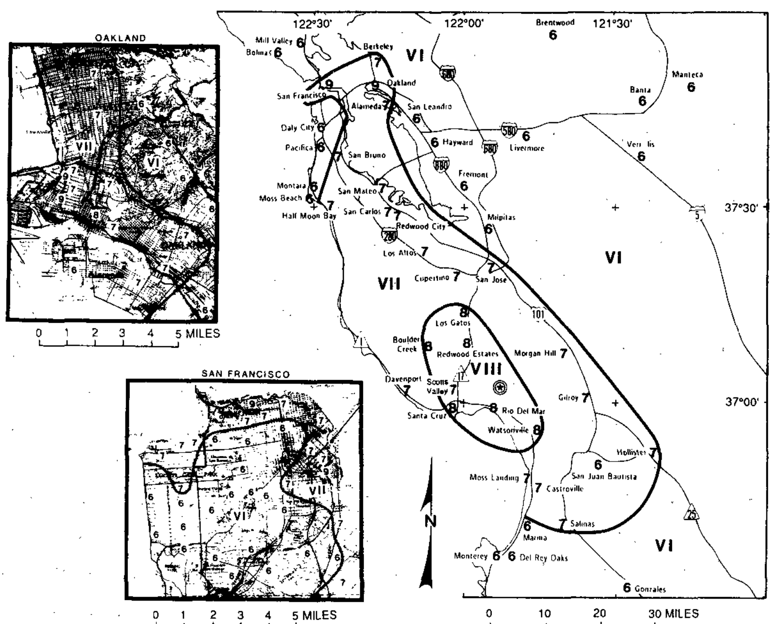


Fig. 1 Distribution of seismic intensity in the San Francisco Bay Area.

According to the intensity scale in Table 1, destruction of the ground, such as landslides, sand blown up, and liquefaction generally occurs at levels IX or higher on the MM scale. However, surveys and the observation carried out after the proposal of this intensity scale indicate that this type of phenomena could occur already at a lower level of seismic intensity,

Table 1 Modified Mercalli Intensity Scale.

Intensity	Contents	Acceleration
I	Noticed only by few people in especially sensitive situations.	0.5-1.0 gal
II	Noticed only by a few people, such as those resting in the upper stories of buildings. Movable objects shake.	1.0-2.1 gal
III	Clearly noticeable, especially indoors in the upper stories of buildings. Stopping cars shake slightly, but many people don't consider it an earthquake.	2.1-5.0 gal
IV	In daytime, many people indoors feel the shaking. Dishes, window panes and doors tremble, and stopping cars shake considerably.	5-10 gal
V	Almost everyone can feel the quake. Many people wake up.Unstable objects fall down and pendulum clocks stop.	10-21 gal
VI	Everybody feels the quake and many people rush outdoors frightened.	21-44 gal
VII	Most people rush outdoors. Unstable and badly designed objects are damaged to a certain degree.	44-94 gal
VIII	Solid buildings are damaged considerably. Chimneys, monuments and walls collapse, furniture falls over. Gritty mud spurts out abundantly; changes occur in well water.	94-202 gal
IX	Solid buildings are damaged and partly destroyed. The ground cracks in several places.	202-432 gal
X	Most parts of masonry buildings collapse. More and larger cracks appear in the ground; railways are bent.	over 432 gal
XI	Only few buildings remain intact, bridges are damaged and large cracks in the ground open up.	-
XII	Everything is destroyed. Waves appear on the surface of the ground and some things are thrown up in the air.	-

depending upon ground water content, permeation and solidity of the ground, and the physical properties of the solid materials covering the surface of hilly land and cliff slopes. This suggests that intensity can hardly be evaluated properly from the above mentioned ground destruction phenomena alone. The distribution of intensity (MM scale) in Fig. 1 is therefore determined from the damage to buildings and structures, and the areas thought to be affected by ground destruction phenomena are evaluated by reference to destruction of other structures in the surrounding area.

Thus, the cities Santa Cruz, Los Gatos, Watsonville and Redwood Estates are rated VIII (MM scale) based on badly destroyed wooden houses and unrein-forced masonry buildings. Moreover, the highest seismic intensity level is recorded in the local areas of San Francisco and Oakland. The destruction of the double floor structure at I − 880 Cypress Street in Oakland and the huge damage to I − 280 Embarcadero in San Francisco are definitely to be attributed to level Ⅸ tremors (MM scale).

Also, the Marina district in northern San Francisco is assigned a Ⅸ (MM scale). In this distict, quake intensity as well as ground destruction are seen affecting the destruction of several apartments, but the damage to many other structures in the area occurred without and definite ground destruction phenommena. Therefore, from the collapse of those types of structures and the structural damage to many buildings in the surrounding area, the Marina district is evaluated as level Ⅸ (MM scale).

In the area described above, destruction seemes to be linked to reclaimed land and relatively new, soft ground. Similarly, the intensity in eastern and northern San Francisco, an area covered with alluvium and bay mud, is between 1 and 3 points higher on the MM scale than that recorded in other parts of San Francisco. The intensity for the westernmost part of San Francisco is Ⅶ, the same as for the center of the city, because these regions are covered with a relatively thick sedimentary bed (Fig. 1).

Because of the different intensity scales, comparison between the intensity distribution of the Loama Prieta earthquake and that of San Francisco in 1906 is very difficult, but there is some evidence for more intensive shaking having occurred in the 1906 quake. This can be seen particularly along the segment of the peninsula in the northern San Andreas fault, and the surroundings of San Francisco Bay. Also, very close to the hypocenter of the Loma Prieta earthquake, in the Santa Cruz Mountains and the area around Monterey Bay, there are clear differences in the distribution of intensity for both quakes.

This could have resulted from the different hypocentral positions and magnitudes of the quakes, but in the 1906 San Francisco earthquake, the isoseismal zone rated Ⅷ (MM scale) at the center of the destructive area of the San Andreas fault extended into the northern part of the region rated Ⅶ in the 1989 Loma Prieta earthquake. Moreover, there is a big difference in the surrounding areas of San Fracisco Bay. Most of this area consists of bay mud, and while it belonged to the isoseismal zone of Ⅷ through X in the 1906 San Francisco quake, with exception of some places in San Francisco and Oakland with locally recorded levels of Ⅸ, most of it registered only levels Ⅵ-Ⅶ (MM scale) in the Loma Prieta earthquake.

2. 2. The zoning map of the bay area

Many earthquakes have occurred in California, on the west coast of the U.S. Therefore, the USGS predicts maximum intensity for the San Andreas Fault and Hayward Fault. Fig. 2 shows the product of this prediction : the zoning of San Francisco according to a 5 level intensity scale from A to E (Table 2) on a map of 1 : 125000. This intensity scale was obtained from the destruction and ground condition at the time of the 1906 San Francisco quake (Fig. 3, Fig. 4). It also corresponds to Rossi-Forel intensity scale and the

Modified Mercalli intensity scale (Fig. 5).

The above prediction of maximum intensity was made in view of the amplification ratio from the nature of the soil and the ground condition, based on the relation between the epicentral distance (the shortest distance from the fault) and intensity for the 1906 San Francisco quake, and the analysis of the earthquake record of low distortion observed at the nuclear experiment in Nevada. In anticipation of a big earthquke at both the San Andreas Fault and Hayward Fault, maximum intensity is predicted by accepting the larger numerical value.

This zoning map leaves a few questions to be discussed below, but it is considered useful for the administrative policy of land utilization, in the sense that is clearly specifies the high risk disaster regions in case of a strong earthquake at both faults. However, in terms of exactly evaluating the safety of individual structures, the risk of liquefaction in areas consisting of soft ground such as bay mud is not necessarily accounted for. A more detailed survey would involve the study of various maps that show the active faults and indicate the risk of liquefaction and landslides.

The zoning map of Fig. 2 is considered very useful as a zoning map that specifies the high risk areas in an earthquake disaster described above. In the case of the Loma Prieta earthquake, the high intensity areas of San Francisco Bay involving the city of San Fancisco and Oakland are obviously identical to the relatively high risk area (B zone) indicated in the zoning map. Thus, to reduce earthquake disaster, this type of zoning maps are expected to be fully utilized by the administrative authorities.

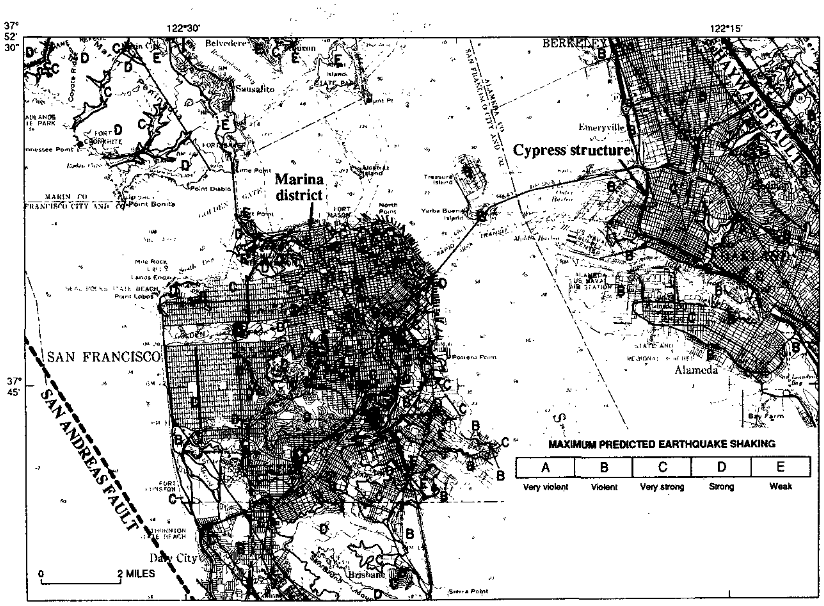


Fig. 2 Microzoning map of San Francisco City and its vicinity.

Table 2 San Francisco Intensity Scale.

San Francisco Intensity Scale for 1906 Earthquake

GRADE	DAMAGES
Grade A. Very violent	Comprises the rending and shearing of rock masses, earth, turf, and all structures along the line of faulting; the fall of rock from mountainsides; numerous landslips of great magnitude; consistent, deep, and extended fissuring in natural earth; some structures totally destroyed.
Grade B. Violent	Comprises fairly general collapse of brick and frame buildings when not unusually strong; serious cracking of brick-work and masonry in excellent structures; the formation of fissures, step faults, sharp compression anticlines, and broad, wavelike folds in paved and asphalt-coated streets, accompanied by the ragged fissuring of asphalt; the destruction of foundation walls and underpinning structures by the undulation of the ground; the breaking of sewers and water mains; the lateral displacement of streets; and the compression, distension, and lateral waving or displacement of well-ballasted streetcar tracks.
Grade C. Very strong	Comprises brickwork and masonry badly cracked, with occasional collapse; some brick and masonry gables thrown down; frame buildings lurched or listed on fair or weak underpinning structures, with occasional falling from underpinning or collapse; general destruction of chimneys and of masonry, brick, or cement veneers; considerable cracking or crushing of foundation walls.
Grade D. Strong	Comprises general but not universal fall of chimneys; cracks in masonry and brick-work; cracks in foundation walls, retaining walls, and curbing; a few isolated cases of lurching or listing of frame buildings built upon weak underpinning structures.
Grade E. Weak	Comprises occasional fall of chimneys and damage to plaster, partitions, plumbing, and the like.

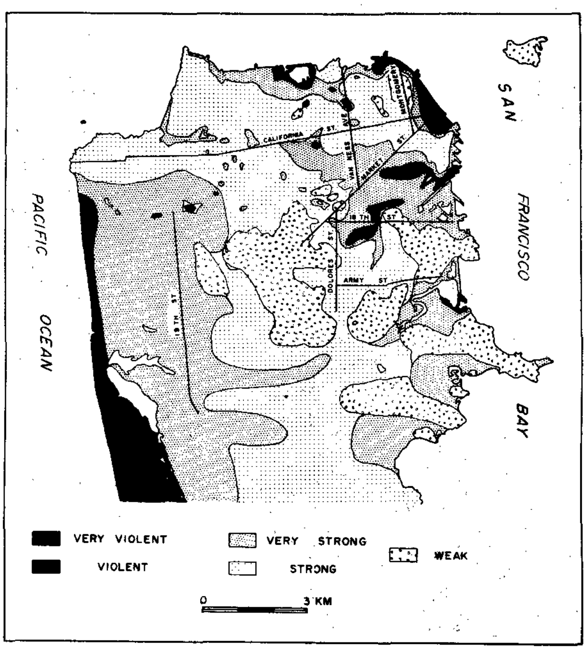


Fig. 3 Intensity distribution in San Francisco City at the 1906 San Francisco Earthquake.

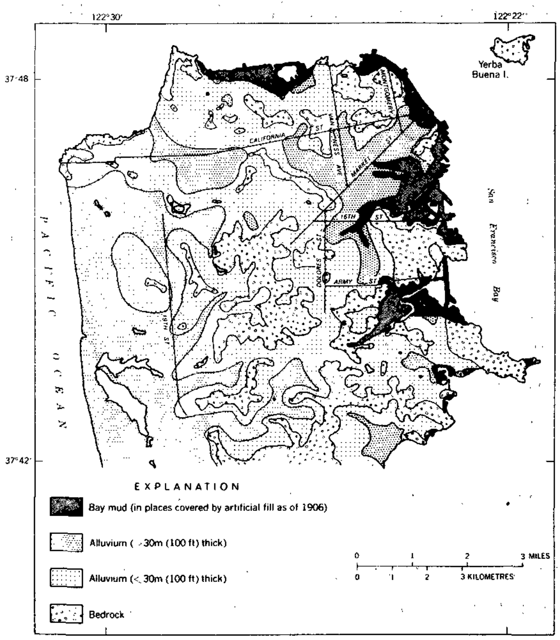


Fig. 4 Classfication of ground condition in San Francisco City.

A

San Francisco scale	Rossi-Forel scale
Grade A	10
Grade B	10
Grade B	9
Grade C	8
Grade D	8
Grade D	7
Grade E	7

B

Rossi-Forel scale	Modified Mercalli scale
10	X-XII
9+	IX
8+ to 9-	VIII
8-	VII
6 to 7	VI

Fig. 5 Comparison of the various seismic intensity scale.

3. Distribution of seismic intensity calculated from the questionnaire survey in San Francisco

3. 1. Purpose of survey

The aim of this survey is first to scrutinize the intensity distribution within the city of San Francisco and second to confirm the influence of subsurface geology and prove the credibility and efficiency of the questionnaire based MM intensiy survey method.

The city of San Francisco spans about 12 km from north to south and 15 km from east to west. The epicenter of the last major earthquake was 92 km, the edge of the aftershock region 72 km away. California (San Andreas Province) has the following standard formula for calculating the decrease of seismic intensity (Chandra, 1979) :

$$I(R) - Io = 2.014 - 0.00659R - 2.014\log(R + 10) \qquad R < 330 \text{ km} \qquad (1)$$

R = epicentral distance, Io = epicentral intensity,
I(R) = intensity at epicentral distance R.

Substitulting Io = 8, R = 92 − 6 = 86 and R = 92 + 6 = 98, we get I(86) = 5.45, I(98) = 5.27.
(Substitulting Io = 8, R = 72 − 6 = 66 and R = 72 + 6 = 78, we get I(66) = 5.79, I(78) = 5.27)

Thus, the difference in intensity between the north and the south of the city amounts to only about 0.2 and is negligible in the discussion of local site effects.
(But we have to drop the decrease member from the equation when dealing with the intensity differences of 0.2)

3. 2. Method of survey

(1) Time period and area of survey

The field survey, distribution of questionnaire forms and some inquiries, took us five days, from Novemver 27 to December 1, 1989. The area of survey was limited to the city of San Francisco.

(2) The questionnaire

The questionnaire used was one already preapared for surveying seismic intensity in California (Ohashi et al., 1987) ; it is based on the definitions of the Modified Mercalli scale, with additional reference to the MSK scale. It has a total of 34 items, 21 of which directly concern the rating of intensity. Fig. 6 shows the questionnaire form.

In the U.S., USGS conducts routine questionnaire surveys on intensity by mail whenver a disastrous earthquakes occurs, for the purpose of creating a macroscopic map of intensity distribution. The standard USGS questionnaire covers as many as 58 items in great detail,

11. Did you feel the earthquake ?
    1 yes 1 [ ]
    2 no 2 [ ]

12. How many of those around you felt the shaking ?
    1 nobody 1 [ ]
    2 a few 2 [ ]
    3 many 3 [ ]
    4 all 4 [ ]
    5 don't know 5 [ ]

13. If anyone was sleeping, did the sleeping people awake ?
    1 a few people woke up 1 [ ]
    2 many woke up 2 [ ]
    3 all woke up 3 [ ]
    4 no one was sleeping 4 [ ]

If you did not feel the earthquake, you can finish.
Thank you very much.

14. Would you say the vibration you felt was
    1 light 1 [ ]
    2 moderate 2 [ ]
    3 strong 3 [ ]
    4 violent 4 [ ]

15. How long do you think the shaking lasted ?
    1 sudden (less than 10 seconds) 1 [ ]
    2 short (10 - 30 secs) 2 [ ]
    3 long (30 - 60 secs) 3 [ ]
    4 very long (more than 1 min) 4 [ ]

16. Were you frightened during the shaking ?
    1 not at all 1 [ ]
    2 a little bit 2 [ ]
    3 quite 3 [ ]
    4 almost panic 4 [ ]

17. What did you do during the shaking ?
    1 stayed where I was 1 [ ]
    2 tried to protect myself, someone else or some valuables 2 [ ]
    3 moved to another room 3 [ ]
    4 tried to exit building 4 [ ]
    5 other (please specify) 5 ____________

18. If you tried to, was it difficult to move ?
    1 easy to move 1 [ ]
    2 difficult but possible to move 2 [ ]
    3 couldn't move 3 [ ]
    4 fell down 4 [ ]
    5 didn't try to move 5 [ ]

19. Was the vibration noticed in your car ?
    1 not in a car 1 [ ]
    2 noticed in parked car 2 [ ]
    3 noticed in moving car 3 [ ]
    4 difficult to control car 4 [ ]

20. Did you see any trees, poles or parked cars move ?
    1 none moved 1 [ ]
    2 some moved slightly 2 [ ]
    3 some moved violently 3 [ ]
    4 branches broke off 4 [ ]
    5 don't know 5 [ ]

LOMA PRIETA EARTHQUAKE INVESTIGATION PROJECT
ARCHITECTURAL INSTITUTE OF JAPAN (AIJ)

This is a survey of the Loma Prieta Earthquake of October 17, 1989. It aims to define and compare the distribution of shaking in this earthquake, and to prepare for future earthquakes. Your input is very important for the success of this project.
Please go down the pages answering the questions for this earthquake.
Thank you very much for your kind cooperation.

1. When the earthquake occurred, you were check
    1 in your town 1 [ ]
    2 somewhere else 2 [ ]

2. The address where you were located at the time of the earthquake, if known
    street ____________
    city ____________
    state,zip ____________
    If not, approximate location is ____________

3. The place was
    1 flat land 1 [ ]
    2 on a top of hill 2 [ ]
    3 on a slope 3 [ ]
    4 in a valley 4 [ ]

4. You were
    1 indoors 1 [ ]
    2 outdoors 2 [ ]
    3 in a vehicle 3 [ ]

5. Check your activity when the earthquake occurred
    1 moving 1 [ ]
    2 standing 2 [ ]
    3 sitting 3 [ ]
    4 lying down 4 [ ]
    5 sleeping 5 [ ]
    6 other (please specify) 6 ____________

6. If you were inside a building, the type of building was
    1 house 1 [ ]
    2 mobile home 2 [ ]
    3 apartment 3 [ ]
    4 office 4 [ ]
    5 shop 5 [ ]
    6 other (please specify) 6 ____________

7. What was the building mainly made of ?
    1 brick or block 1 [ ]
    2 wood 2 [ ]
    3 concrete 3 [ ]
    4 steel 4 [ ]
    5 other (please specify) 5 ____________

8. How old is the building ?
    1 built before 1935 1 [ ]
    2 built between 1935 and 1965 2 [ ]
    3 built between 1965 and 1975 3 [ ]
    4 built after 1975 4 [ ]
    5 don't know 5 [ ]

9. How many floors did the building have ? ________

10. What floor were you on ? ________

21. Did hanging objects like pictures and lamps swing ?
- 1 no 1 [ ]
- 2 some moved slightly 2 [ ]
- 3 some moved a lot 3 [ ]
- 4 some fell or were damaged 4 [ ]
- 5 don't know 5 [ ]

22. What happened to windows, doors or dishes ?
- 1 they rattled 1 [ ]
- 2 they swung open or close 2 [ ]
- 3 some dishes broke 3 [ ]
- 4 some windows broke 4 [ ]
- 5 don't know 5 [ ]

23. Did you see the liquids in open vessels move ?
- 1 some moved a little 1 [ ]
- 2 some moved a lot 2 [ ]
- 3 some spilled 3 [ ]
- 4 don't know 4 [ ]

24. Did shelf goods move ?
- 1 none moved 1 [ ]
- 2 a few shifted or overturned 2 [ ]
- 3 many fell off shelves 3 [ ]
- 4 all fell off shelves 4 [ ]
- 5 don't know 5 [ ]

25. What happened to furniture ?
- 1 furniture did not shake 1 [ ]
- 2 it shook slightly 2 [ ]
- 3 it moved a little 3 [ ]
- 4 it moved and overturned 4 [ ]
- 5 considerable damage to furniture 5 [ ]
- 6 don't know 6 [ ]

Questions 26, 27 and 28 refer to your building,
OR to neighboring building if you were outdoors.

26. Damage to walls of the building
- 1 none 1 [ ]
- 2 fine cracks in plaster 2 [ ]
- 3 pieces of plaster fell off 3 [ ]
- 4 there were large and deep cracks 4 [ ]
- 5 one or more walls collapsed 5 [ ]

27. Damage to foundation of the building
- 1 none 1 [ ]
- 2 foundation cracked 2 [ ]
- 3 building moved on foundation 3 [ ]
- 4 building moved off foundation 4 [ ]
- 5 foundation destroyed 5 [ ]
- 6 don't know 6 [ ]

28. Was there damage to chimneys, parapets and ornaments ?
- 1 none 1 [ ]
- 2 some cracked 2 [ ]
- 3 some fell 3 [ ]
- 4 most fell 4 [ ]
- 5 don't know 5 [ ]

29. Was there damage to stone or brick walls, tombstones or monuments in neighborhood ?
- 1 no damage 1 [ ]
- 2 small cracks 2 [ ]
- 3 big cracks 3 [ ]
- 4 collapses 4 [ ]
- 5 don't know 5 [ ]

30. Were there ground cracks, rockfalls and landslides in your neighborhood ?
- 1 none 1 [ ]
- 2 few 2 [ ]
- 3 many 3 [ ]
- 4 numerous 4 [ ]
- 5 don't know 5 [ ]

31. Was your telephone, water, gas or electricity interrupted after the earthquake ?
- 1 no interruption 1 [ ]
- 2 for a few hours 2 [ ]
- 3 for a few days 3 [ ]
- 4 for a week 4 [ ]
- 5 longer 5 [ ]
- 6 don't know 6 [ ]

32. Was you or your family injured due to the earthquake ?
- 1 no 1 [ ]
- 2 yes, slightly 2 [ ]
- 3 treated by doctor 3 [ ]
- 4 hospitalized 4 [ ]
  (what injury) ______________

33. You are
- 1 male 1 [ ]
- 2 female 2 [ ]

34. How old are you ? ________

By Dr. Toshio MOCHIZUKI

Earthquake Engineering Researcher, Member of AIJ,
Head Researcher of Urban Disaster Prevention and
Security, Center for Urban Studies,
Prof., Tokyo Metropolitan University,
1-1 Yakumo 1-chome, Meguro-ku, Tokyo Japan 152

Dr. Norio ABEKI

Structural Engineering Researcher, Member of AIJ,
Prof., Kanto Gakuin University,
4834 Mutsuura-cho Kanazawa-ku Yokohama-shi Japan 236

and Mr. Takahisa ENOMOTO

Earthquake Engineering Researcher, Member of AIJ,
Research Associate, Kanagawa University,
3-27-1 Rokkakubashi Kanagawa-ku Yokohama-shi Japan 221

Fig. 6 Questinnaire form.

but it targets only public institutions, e. g. post offices, because USGS tries to evaluate the seismic intensity for one spot by a single questionnaire. Our objects of survey where the citizens, the staff of schools and others. The questions and their choices were easy to understand. Different from USGS, we determined the intensity at any spot (each mesh) from the average value of at least several questionnaires.

(3) Distribution and collection of questionnaires

We conducted the survey on the staff of a total of 44 public senior and junior high schools and 2 elementary schools in the city of San Francisco. We visited 12 of the schools directly on November 27-28, 1989, and handed the questionnaire forms to the principals, asking for their cooperation. For the other 38 schools, the person in charge at SFUSD (San Francisco Unified School Distict) kindly sent the forms with SFUSD tags to the principals after November 30. As a rule, we enclosed 50 forms for each senior high school and 30 for each junior high school, and asked the teachers to fill them in.

Besides the schools, we also asked two local construction consulting companies and one travel agency for their cooperation, and so the toal number of questionnaire forms passed out amounted to about 2,000 to 47 institutions.

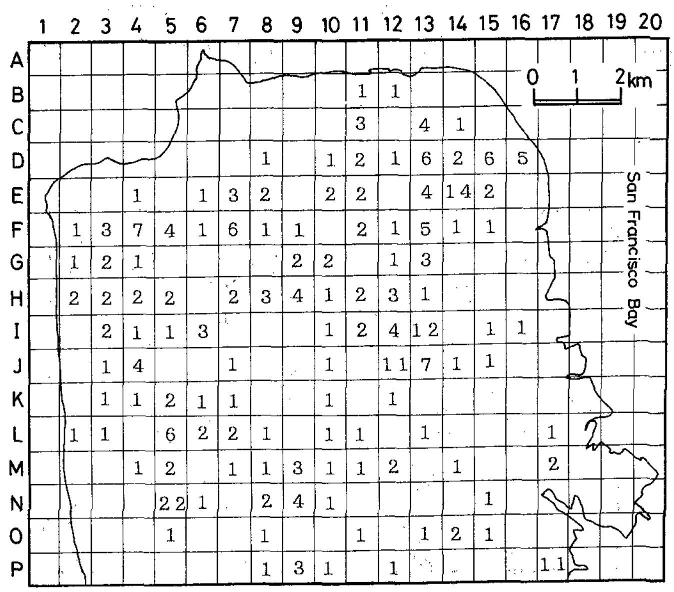


Fig. 7 Distribution of retreval questionnaire sheets.

We asked them to mail the forms back to Japan (we gave stamped, self-addressed envelopes together with the forms). By Febuary 16, 1990, we had received a total of 515 forms from 27 institutions (two companies and 25 schools.) Among them, 290 were complete enough to establish the replier's position in the city at the very time of shaking, even up to the house number. There were 96 replies from within the city without house number or street address filled in. There were 81 forms from places other than the city of San Francisco and 48 with no location given. Fig. 7 shows the distribution over San Francisco of the 290 valid forms.

(4) Data

As mentioned above, we got 290 complete questionnaires with specific location in the city at the time of the earthquake. There were 96 others from the city without exact location, 81 from outside the city, and 48 giving no location at all.

We divided San Francisco into meshes with 16 partitions (A-P) from north to south and 20 from east to west. One mesh is a regular square of about 750 m side length. The subsurface geological map in Fig. 4 shows the geological composition of the city of San Francisco as follows :

(1) Bay mud (Qm : Holocene estuarine mud, reclaimed mud)

(2) Quaternary alluvium (Qual)

(3) Bedrock (Kjf : Franciscan Formation).

For comparison with the intensity values given in the questionnaires, we read the geological composition of each mesh and added 2 more intermediate categories :

(1.5) mixture of bay mud and alluvium deposits

(2.5) mixture of alluvium deposits and bedrock.

Where one mesh contains 3 types of ground and where bay mud and bedrock meet, no value was assigned. (P-17, Candlestick Park baseball ground, was treated as bay mud).

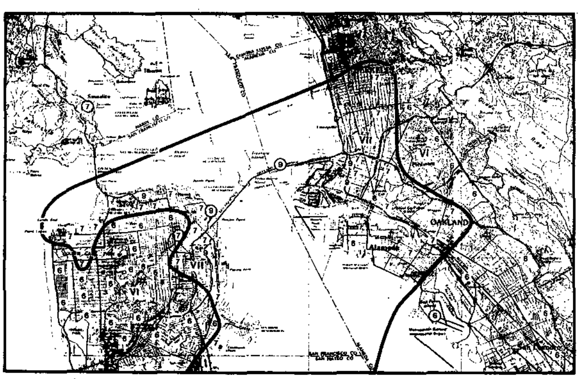


Fig. 8 Distribution o seismic intensity in San Francisco City and Orkland City evaluted by USGS.

We counted the number of dangerous buidings for each mesh from among 164 buildings in the city labeled 'dangerous' on the distribution map (Fig. 5.3.2.1 A.I.J.Report) and set it against the intensity as damage indicator. The damage indicator was released by the San Francisco municipal authorities after their field inspection carried out from Ocotober 18 to November 2 (but it is not certain if the inspection covered the whole city).

USGS published an MM scale contour map (Fig. 8. Plafker and Galloway, 1989) based mainly on data from the field inspection supplemented by early responeses from a mail survey. The map shows that most of San Francisco is rated VI, the north and the coastal part of the east VII, and the Marina and the South Market districts IX, because of the serious damage to the higway and the collapse of wooden apartment houses. The data are also compared mesh by mesh.

3. 3. Findings

(1) "Fuzzy" calculation of seismic intensity

The intensity coefficient for every item and category is given in form of a membership function, centering on the most reliable seismic intensity value, allowing a certain latitude. We choose the most appropriate out of 3 functions :

Z function = lower than a given intensity
P function = a cone
S function = higher than a given intensity

For the Z and S functions, emphasis is on the intensity level at the border. Fig. 9 shows an example of a membership function. Table 3 shows, for every item and category, the type of function, the peak intensity coefficient and the function's width of intensity.

We add up the intensity coefficients corresponding to the items and categories marked on one questionnaire and look for the maximum intensity in the entire distribution. Where distribution is discontinuous, we take the average from the intensities to the right and to the left. There might be less scattering if we take the medium rather than the peak value of the distribution.

(2) Results of seismic intensity calculation

i) Average intensity and distribution, comparison with USGS intensity, and comparison with strong motion records

The average fuzzy questionnaire intensity for the 290 cases is 6.0, and its standard deviation is 1.9. Fig. 10 shows the frequency distribution. Comparison to USGS intensity values of VI for the city and VII for both the east coast and the north, shows that this result is valuable.

ITEM	CATEGORY	FUNCTION	MEAN	WIDTH	LABEL (Hanging objects)
21	1	2	20	30	no swing
21	2	2	40	20	slight
21	3	2	60	30	a lot
21	4	3	90	30	fell

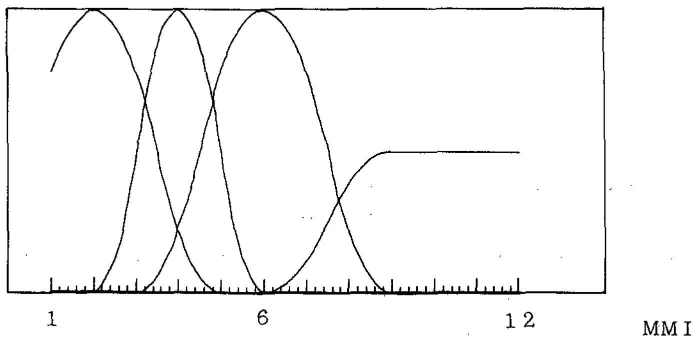
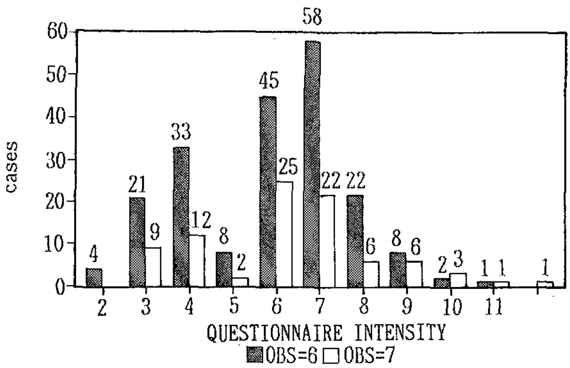


Fig. 9 Sample of the membership function of Fuzzy Intensity.

Table 3 Intensity coefficients for each question item and category.

QUESTION		CATEGORY 1			2			3			4			5		
No	Item	F	P	W	F	P	W	F	P	W	F	P	W	F	P	W
11	Feel quake	S	6	4	Z	1	4									
12	Others feel				P	2	3	P	5	3	S	7	3			
13	Awaken	P	2	3	P	5	3	S	8	3						
14	Vibration	P	2	3	P	5	3	P	7	3	S	9	3			
15	Duration	P	2	3	P	3	3	P	6	3	S	8	3			
16	Frighten	P	3	4	P	5	3	P	7	3	S	10	3			
17	Human behavior				P	6	3	P	6	3	P	8	3			
18	Moving	P	3	4	P	7	3	S	10	4	S	11	3			
19	Car vibration				S	7	4	P	8	3	S	10	3			
20	Tree,pole,car	P	3	4	P	6	2	P	8	3	S	10	3			
21	Hanging objects	P	2	3	P	4	2	P	6	3	S	9	3			
22	Windows,dishes	P	3	3	P	6	3	S	8	3	S	10	3			
23	Liquids	P	3	3	P	6	3	S	9	4						
24	Shelf items	P	3	4	P	6	3	P	8	3	S	10	3			
25	Furniture	P	3	4	P	5	3	P	8	3	P	11	3	S	12	3
26	Walls	Z	4	3	P	7	3	P	8	3	P	10	3	S	12	3
	Wall pre 1935	Z	4	3	P	7	3	P	8	3	P	10	3	S	12	3
	Wall 35-65	Z	5	3	P	8	3	P	9	3	P	11	3	S	13	3
	Wall aft 65	Z	6	3	P	9	3	P	10	3	P	12	3	S	14	3
27	Foundation	Z	5	3	P	8	3	P	10	3	P	11	3	S	13	3
28	Chimneys	Z	5	4	P	8	3	P	10	3	S	12	3			
29	Stone,brck wall	Z	5	4	P	8	3	P	10	3	S	12	3			
30	Ground Cracks	Z	6	3	P	9	3	S	11	3	S	12	3			

F: Function, P: Peak intensity, W: Width of intensity



	mean	59.0	62.2
FZY	std	18.3	19.6
	ncase	202	87
GEO	mean	2.13	1.84
	std	0.29	0.56
DMG	mean	0.31	2.17
	std	0.79	2.62

Fig. 10 Comparison of Fuzzy Intensity and USGS Intensity.

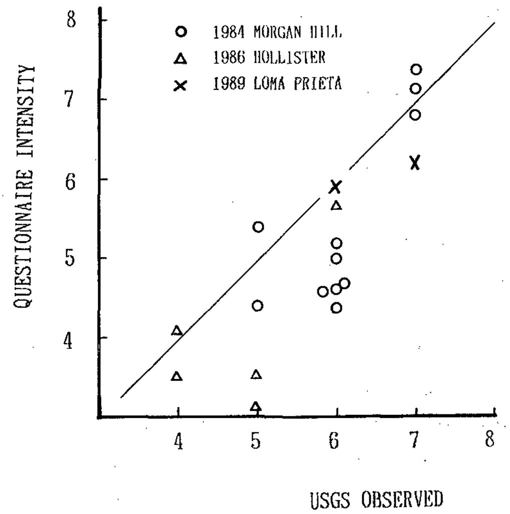


Fig. 11 Comparison of Fuzzy Intensity, geology and sesmic damage.

Table 4 Strong motion data recorded in San Francisco City.

Station name	Peak values H1 g	V g	H2 g	Distance km	Mesh	Geology
1295 Shafter St.	0.11	0.05	0.07	89	M16	hard rock
S.U.,Thornton Hall	0.14	0.04	0.11	93	N5	alluvium
575 Market(bsmt) (0.23)	0.08	0.06	0.11	96	D15	alluvium
600 Montogmery (bsmt)(0.31)	0.12	0.05	0.11	97	D15	alluvium
Diamond Heights	0.12	0.05	0.10	99	K10	rock
Golden Gate Bridge	0.12	0.06	0.24	100	A6	rock
VA hospital (bsmt) (0.34)	0.08	0.05	0.16	100	E2	rock
Rincon Hill	0.09	0.03	0.08	102	?	rock
6-story Bldg(0.28)	0.09	0.04	0.07	103	?	
Telegraph Hill	0.08	0.03	0.06	104	C15	rock
Pacific Heights	0.06	0.03	0.05	104	?	rock
Presidio	0.21	0.06	0.10	105	?	?
Cliff House	0.11	0.06	0.08	107	F1	rock

max component of PGA: 13 cases, 0.13g, s.dev=0.05
alluvium site: 3 cases, 0.12g, s.dev=0.02
rock site: 8 cases, 0.12g, s.dev=0.06

Sorting the meshes of USGS intensity Ⅵ and Ⅶ and averaging the questionnaire intensity, we obtained the values 5.9 (std = 1.8) and 6.2 (std = 2.0) respectively. The difference was fairly small and unstable. We applied this fuzzy intensity calculation method also to the data of the 1984 Morgan Hill and 1986 Hollister earthquakes (Ohashi it al., 1987) and arrived at Fig. 11 by comparing those values with the USGS intensity. In spite of some scattering, the fuzzy questionnaire intensity correlates well with the USGS intensity, the absolute values are also in agreement. In the case of Loma Prieta, however, the fuzzy intensity seems too low against the Ⅶ of USGS.

Strong motion was recorded at 13 points in San Francisco on the ground or in buildings on the ground floor and in basements (Table 4) ; the average of the maximum acceleration amounts to 0.13g (EERI, 1989). The average intensity MM 6 (=JMA 4) in the city corresponds to PGA 0.13 g. The strong motion data for both the 3 points on alluvium and the 8 points on rock averaged 0.12 g, with almost no difference in maximum acceleration. There are no data on the Bay mud. It is also clear from the early USGS report (Plafker and Galloway, 1989) that acceleration is certainly great for Bay mud but not definite for alluvium and rock. The report explains that even if acceleration is the same it lasts longer on alluvium ; thus in relation to velocity and displacement, intensity on alluvium might be greater. It may be wrong to measure intensity differences, that is intensity of earthquake motion, only in terms of acceleration.

ii) Effects of the ground

Table 5 Effects of site geology on Fuzzy questionnaire intensity, USGS observed intensity and damage index.

		1 Bay mud	2 Alluvium	2.5 Mix(Alluv + rock)	3 Bedrock
	Cases	21	214	31	21
Quest. Intensity	Mean	6.72	6.08	5.78	4.74
	St.Dev	1.92	1.88	1.70	1.43
USGS Intensity	Mean	7.00	6.24	6.12	6.33
	St.Dev	0.00	0.43	0.33	0.47
Damage of Buildings	Mean	1.28	0.97	0.00	0.19
	St.Dev	1.63	1.82	0.00	0.39

Table 6 Relative expected intensity for ground condition units in California.

Derived from geologic map of California:	
A. Granitic and metamorphic rocks	-3.00
B. Paleozoic sedimentary rocks	-2.60
C. Early Mesozoic sedimentary rocks	-2.20
D. Cretaceous through Eocene sedimentary rocks	-1.80
E. Undivided Tertiary sedimentary rocks	-1.70
F. Oligocene through middle Pliocene sedimentary rocks	-1.50
G. "Pliocene-Pleistocene" sedimentary rocks	-1.00
H. Tertiary volcanic rocks	-2.70
I. Quaternary volcanic rocks	-2.70
Alluvial units based on depth in feet to water table:	
J. 0 ft< water table < 30 ft	0.00
L. 30 ft < water table < 100 ft	-1.00
M. 100 ft < water table	-1.50

Table 5 shows the relation between intensity and subsurface geology. Seismic intensity obviously tends to be higher in soft ground in the following manner ;

	Bedrock <	Alluvium & bedrock <	Alluvium <	Bay mud
	4.7	5.8	6.1	6.7
difference	(-2.0	-0.9	-0.6	0.0)

Table 6 shows the relative expected intensity for ground condition units in California derived from the 1 : 250000 geological map of California (Ziony, 1985). For a ground water level of 0-30 ft in Bay mud (saturated alluvium) intensity is expected to gain 0.0 ; for a ground water level of 30-100 ft in alluvium the expected gain in intensity is - 1.00 ; for rock like the Frnciscan Formation (early Mesozoic sedimentary rock) the expected intensity gain is - 2.20. The results of our fuzzy questionnaire survey correlate well to this empirical formula.

USGS intensity, on the other hand, is as follows : especially high for Bay mud but without definite order for the other three.

Alluvium & berdrock ≦	Alluvium ≦	Bedrock <	Bay mud
6.1	6.2	6.3	7.0

For this reason, USGS intensity is so flat (contoured) that it hardly reflects more complicated ground conditions.

Almost no correlation was found between questionnaire intensity and the number of dangerous structures per mesh. It seems that the distribution of damaged buildings could be determined from the product of quake force input (intensity) and the distribution of old buildings.

iii) Distribution of intensity

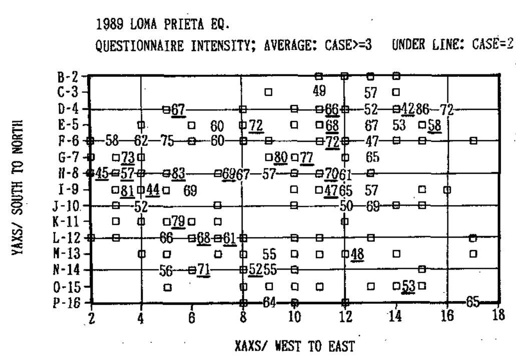


Fig. 12 Distribution of Fuzzy Intensity in San Francisco City.

Fig. 12 shows the average fuzzy intensity for every mesh. The distribution is so complicated and varies so widely that we can hardly pick out any tendencies from it. Therefore, we applied the method of automatic levelling to it (Kagami, 1981), so that we could extract some characteristics of intensity distribution. Fig. 13 is a map drown along isoseismal lines taking in data from a radius of 4 km. However, weight was given to data depending on the distance from a cross obtained throug levelling according to the formula $W = 1 - (Ri/R)^2$. This contour map (R = 4 km) tells us the following:

(1) Comparison with the subsurface geological map shows that Bay mud falls into line with intensity Ⅷ or higher and rock to intensity V or lower. However, no isoseismal lines appear in the contour map around the Bay mud of K. 16-18 and G. 15-17. The reason may be that we could not collect many questionnaires from this area.

(2) Alluvium falls into two categories, one with intensity Ⅶ (Sunset District) and the other with Ⅵ. This is supposed to be related to the depth of alluvium and the level of ground water.

(3) Contour Ⅶ is almost identical to that of the USGS intensity distribution map, but the intensity for the South Market area is not very high. There is no intensity V for rock in USGS intensity: the fuzzy intensity may be somewhat too small.

(4) To get a more detailed intensity distibution, we took in data from a radius of only 2 km and contoured. But because of lack of questionnaires, the fluctuation was too strong to grasp any tendency.

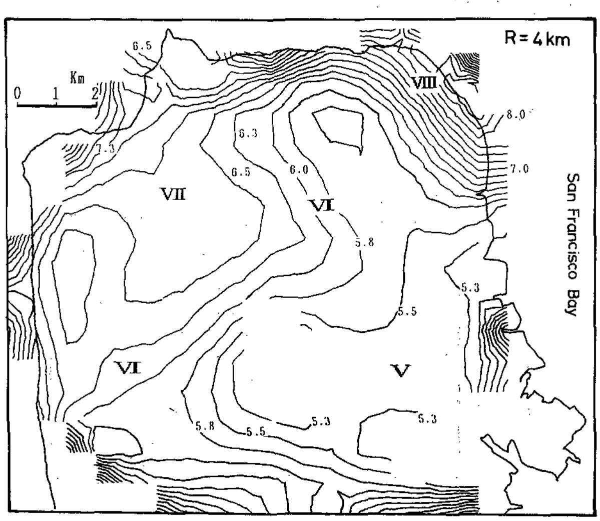


Fig. 13 Isoseismal map in San Francisco City.

4. Summary

We rendered a micro-distribution of intensity for the city of San Francisco by using fuzzy intensity, and in this way also examined the credibility of fuzzy intensity calculation. While a certain credibility could be establishied, it is necessary to collect quality data for further examination. In this survey there was a lack and bias of data, making it impossible to survey as minutely as we could have, had we performed microzoning all over the city of San Francisco. Subsurface geology clearly has an effect on intensity, and it can explain intensity distribution in San Francisco.

Reference literature

1) Chandra, U.(1979) : Attenuation of intensities in the United States, BSSA, 69, 6. pp. 2003 − 2024.
2) EERI (1989) : Loma Prieta earthquake October 17, 1989 Preliminary Reconnaissance Report.
3) George Plafker and John P. Galloway, Editors (1989) : Lessons learned from the Loma Prieta, California, earthquake of October 17, 1989, U.S. Geological Survey Circular 1045. pp. 17 − 20, Ground Shaking-Shaking Intensity.
4) Yoji Kagami H. (1982) : Automatic expression of earthquake-engineering data which distributes in space, Proceedings of the Sixth Japan Earthquake-Engineering Symposium, 1982, pp. 265 − 272.
5) A.I.J. Loma Prieta earthquake damage reconnaissance team (1990) : 1989 Loma Prieta earthquake damage reconnaissance report.
6) Ohashi, H., T. R. Toppozada, M.E.Durkin (1987) : Seismic intensity questionnaire survey for 2 California earthquakes, Presented at the SSA '87 meeting, Santa Barbara.
7) Ziony, J.I., Editor (1985) : Evaluating earthquke hazards in the Los Angeles Region-an earth-science perspective, U.S. Geological Survey Professional Paper 1360.

Key Words (キー・ワード)

Modified Mercalli intensity scale (修正メリカリ震度階), San Francisco Bay Area (サンフランシスコ湾岸地域), Questionnaire survey (アンケート調査), Isoseismal map (等震度地図), Classfication of ground condition (地盤分類)

1989年　ロマ・プリータ地震の震度分布

1989年10月17日午後5時4分（現地時間）に発生したロマ・プリータ地震（M7.1）は、サンフランシスコの南東約110kmのサンアンドレアス断層上を震度として発生した。断層の長さは約40kmで、震度の深さ約18kmとされ、断層上で右横ずれ1.7m, 縦ずれ1.3mの断層運動が確認された。震度近傍地域の市街地の建築構造物の被害はもとより、震源より約100km程度離れた近代的な都市であるサンフランシスコ市やオークランド市において海岸部の埋立地を中心に大きな被害が発生し、特にベイブリッジや高架橋構造の高速道路の崩壊による多くの死傷者やライフライン系の被害など典型的な都市型の被害が生じた市民生活に大きな影響を及ぼした。この地震による人的被害は死者62人、負傷者約3800人であった。また、倒壊建物を含む被災建物数は約3万棟で被害総額は約59億ドルと報告されている。

本地震の震度分布は震源近傍の地域において修正メルカリ震度階で震度8（気象庁震度階6程度）、サンフランスコ市やオークランド市においては同震度7（同5程度）であるが、同地域内において局所的に同震度9（同7程度）の大きな震度分布を示す地域があり、大被害地域となっている。

一方、地震動の強震計観測記録はUSGS（米国地質調査所）とCDMG（カリフォルニア鉱山局）が設置した観測網により多数の地点で貴重な記録が観測されている。震源近傍の地域では、地盤上の水平動成分の最大加速度値が0.64g（Corralitos)、0.54g（Capitola）と大きな値を示し、上下動成分も0.5～0.6gの値を記録している。またオークランド市周辺地域で0.26g (Emeryville)、サンフランシスコ市周辺で0.24g (Golden Gate Bridge)、0.33g（San Francisco Intl. Airport）と報告されている。しかしながら、これらの資料だけからではサンフランシスコ市やオークランド市の市内における地域的に細かな震度分布を評価することは難しい。

米国では、USGSが中心となって、地震の多発するカリフォルニア州のサンフンドレアズ断層に沿う地域、特にサンフランスシコ湾岸地域を対象として、同断層および平行して走るヘイワード断層上に発生する大地震を想定した震度分布予測のためのゾーニングマップが作成されている。これは、地震断層・地質地形・地盤などを考慮して作成されたものであり、特に今回のロマ・プリータ地震でのサンフランシスコ市やオークランド市における被害発生地域は、上記のゾーニングマップにおいて、震度が相対的に高いと予測されていた地域と符合しているように思われる。

本報告では、特に大都市であるサンフランシスコ市においてサイスミックマイクロゾーニングの観点から、アンケートによるミクロな震度分布調査を行い、すでにUSGSにおいて作成されている既往の地盤分類に基づいたマイクロゾーニングマップとの対応について検討を行った。その結果、サンフランシスコ市におけるUSGSによる震度分布は、一部の大被害発生地域の震度を除いてMM震度で7～6程度であったのに対して、地域的に詳しい震度分布のコンターが得られ、表層地盤の性質に対応していることが明かとなった。