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Building Damage and Seismic Intensity in Bam City from the 2003 Bam, Iran, Earthquake

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Abstract

An investigation is carried out on earthquake damage to 839 buildings in and around Bam City, and seismic intensities, using European Macroseismic Scale 1998 (EMS98), are estimated. The northern and eastern sides of Bam City show higher damage rates (more than 80%), than the southern and western sides (20% less). Combining the results and the vulnerability classes of various building types, the estimated MSK intensities are higher (up to XI) at the northern and eastern sides, and lower (down to VIII) at the south and west sides.

Key words : 2003 Bam earthquake, earthquake damage, seismic intensity, European Macroseismic Scale 1998 (EMS98)

1. Introduction

On December 26, 2003 at 05 : 56 (local time), a devastating earthquake with a magnitude of Mw 6.6 (USGS, 2003), 6.5 on the Richter scale, occurred at (29.01°N, 58.26°E), 10 km, southwest of Bam city in Kerman province, southeast Iran (IIEES, 2003), as shown in Fig. 1. It is estimated that more than 26,000 people were killed, 30,000 injured, and up to 75,600 left homeless. About 85% of the housing and the infrastructure were destroyed (UN Office, 2004). The United Nations (UN) estimates that the number of people affected by the loss of economic activity and damage to property and infrastructure is up to 200,000 (UN Office, 2004). To investigate seismological characteristics and earthquake damage, a Japanese reconnaissance team was dispatched to Bam City, with grand-in aid for scientific research from Monbu-Kagaku-sho (Japanese Ministry of Education, Culture, Sports, Science and Technology), Architectural Institute of Japan (AIJ), and Japan Association for Earthquake Engineering (JAEE). The reconnaissance was carried out in collaboration with International Institute of Earthquake Engineering and Seismology (IIEES) of Iran. As members of the team, we investigated more than 800 damaged buildings in and around Bam city. In this paper, we summarize various types of building damage, and estimate seismic intensities using the data collected.

2. Building Damage in Bam City and Strong Ground Motions

Figure 2 shows maps of Bam and Baravat cities, together with the Bam fault, the locations of the strong motion station of Building and Housing Research Center (BHRC) of Iran, and 8 acceleration stations of IIEES for recording aftershocks. The figure also shows an earthquake damage map, which was drawn from aerial photos (National Cartographic Center of Iran, 2003). The eastern side of Bam city, which is closer to the Bam fault, shows higher damage rates than the western side of the city. The Bam fault is considered to be the causative fault of the Bam earthquake, even though the epicentral area of the earthquake is probably south of the city (IIEES, 2003).

Figure 3 shows strong motion records and their response spectra at the Governmental Office in Bam city (see the location of the station in Fig. 2). Figures 3 (a) and (b) show accelerations and velocities. The most interesting characteristic of the record is the

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Fig. 1. Map of Iran and the 2003 Bam Earthquake.

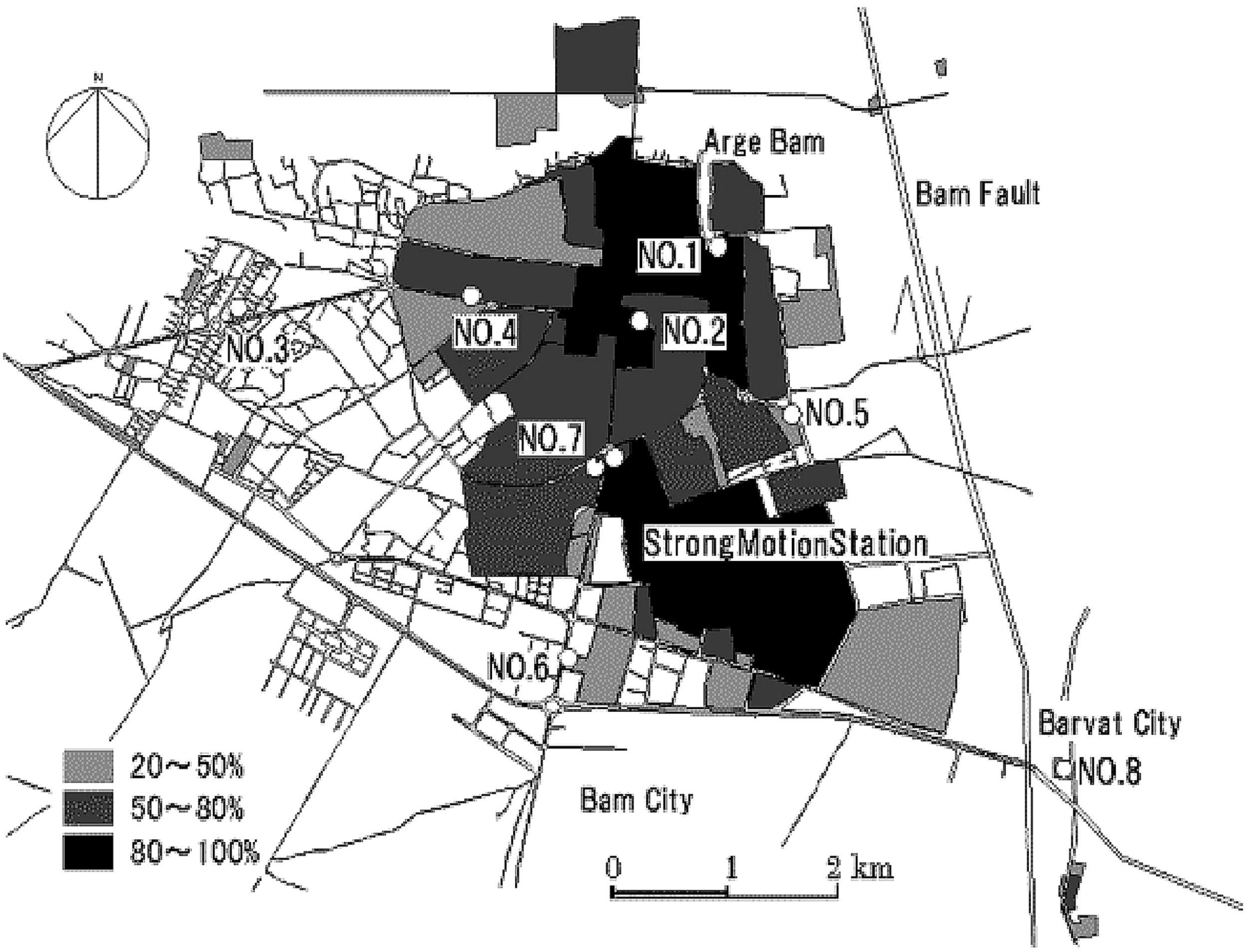
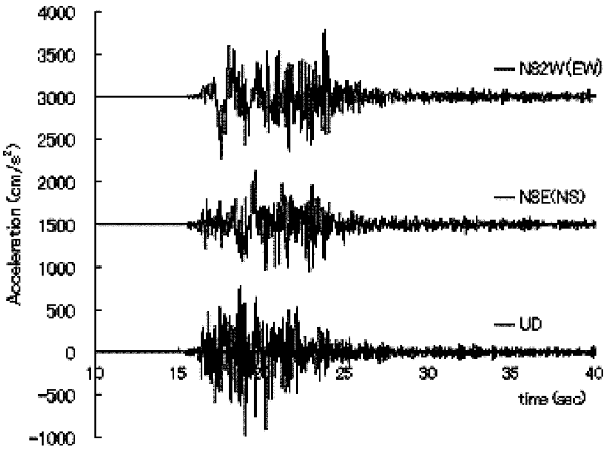
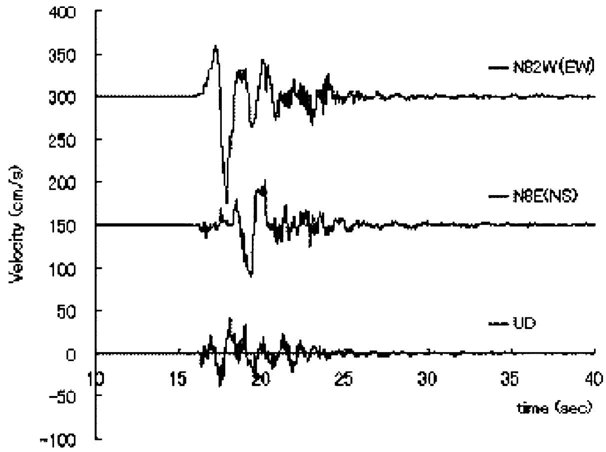


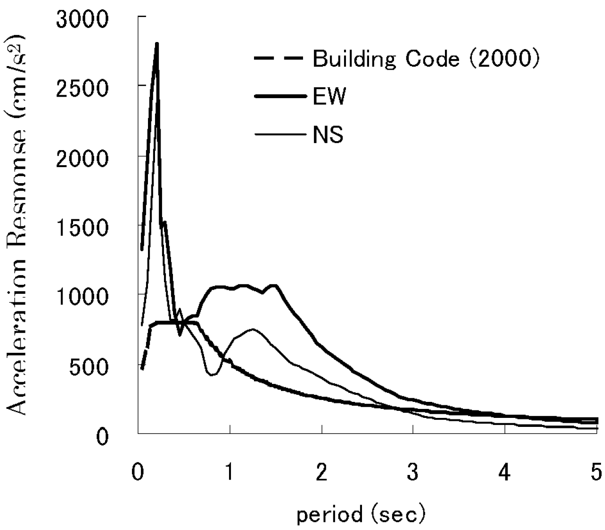
Fig. 2. Earthquake damage map of Bam and Baravat cities[4] and the strong motion and aftershock stations.



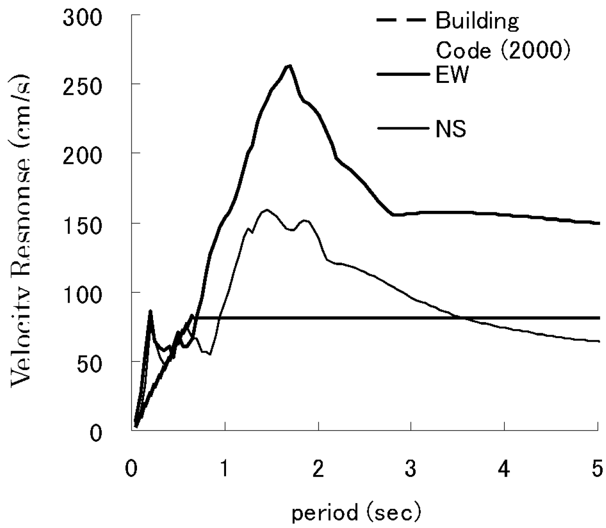
(a) Acceleration.



(b) Velocity.



(c) Acceleration response spectra.



(d) Velocity response spectra.

Fig. 3. Strong motion records and response spectra at the Bam city.

long-period pulse in the EW (N82E) components of the velocities. As can be seen in the response spectra in Figs. 3(c) and (d), the dominant period of the pulse is about 1 to 2 seconds. Because the EW component corresponds to the normal direction of the Bam fault, it seems that the pulse was generated by the forward directivity effect (the killer pulse ; one of the near-fault effects), which was widely observed in the vicinity of seismic faults, such as the 1979 Imperial Valley and 1994 Northridge, California, earthquakes, and the 1995 Kobe earthquake, Japan. During our investigation, we found that most of the tilted buildings were inclined toward the west (i.e., see Photo 2), which suggests the effects of a long-period pulse.

3. Investigation of Building Damage in Bam City

3. 1 Building Type and Vulnerability Class

To investigate building damage and seismic intensities, we followed the European Macroseismic Scale 1998 (EMS98). EMS98 is a macroseismic scale proposed by European Seismological Commission of International Association of Seismology and Physics of Earth's Interior (IASPEI) in 1998, which was modified from the MSK scale (1964) to be applicable to various modern structures. Similar to the MSK scale, EMS98 categorizes the vulnerability classes of buildings from A to F, as shown in Table 1. We classified the building types in Bam city and their vulnerability classes as follows :

1. Adobe : Vulnerability class A (See Table 1 and

(a) Adobe (Vulnerability class A).

(b) Simple Masonry (Vulnerability class B).

(c) Masonry with Steel Frame (Vulnerability class C).

(d) Masonry with RC Frame (Vulnerability class D).

Photo 1. Adobe houses and masonry, and their vulnerability classes.

Photo 1 (a) ; the weakest type of building, constructed from earth bricks and clay mortar)

2. Simple masonry : Vulnerability class B (See Photo 1 (b) ; the second weakest type of building, constructed from manufactured bricks without reinforcements, and cement mortar)
3. Masonry with steel frame : Vulnerability class C (See Photo 1 (c) ; the building made of manufactured bricks and cement mortar, with reinforcements of steel frames)
4. Masonry with RC frame : Vulnerability class D (See Photo 1 (d) ; building made of manufactured bricks and cement mortar, with reinforcements of RC frames)
5. Steel frame : Vulnerability class D or E (See Photo 2 ; building made of moment-resistant steel frames)
6. RC frame : Vulnerability class D or E (building made of moment-resistant RC frames)

EMS98 also classifies damage to buildings into the following Grades 1 to 5.

Grade 1 : Negligible to slight damage
Grade 2 : Moderate damage
Grade 3 : Substantial to heavy damage
Grade 4 : Very heavy damage
Grade 5 : Destruction

It should be noted that it is not easy to generalize the relation between building type and vulnerability class. For example, simple masonry houses (Class B) in old areas of the city (i.e., Station Nos. 1, 2, and 8) seemed to be much weaker than those in new areas of the city suburbs (i.e., Nos. 3, 6, and 7). Many of the former houses seemed to be vulnerability Class A, rather than class B, whereas some of the latter houses could be Class C. Another example is the case of masonry with steel and RC frame; construction skills, especially welding of steel for columns, beams, and braces, were relatively poor in old areas compared to those in new areas. We do not have any more detailed or quantitative information, therefore, we use the simplified categorizations mentioned above.

3. 2 Investigated Areas and Overall Results

As shown in Fig. 4, we investigated building damage at 8 stations installed for recording aftershocks by IIEES. Table 2 shows a list of the stations, their locations, and numbers of buildings investigated in each area. For maps of Bam city, we used satellite images of Quick Bird, whose resolution is about 5 m and is sufficient to identify each house

(a) Moment-resistant steel frame building.

(b) Close-up of the column-beam connection.

Photo 2. Moment-resistant steel frame building (under construction).

Table 1. Vulnerability class European Macroseismic Scale 1998 (EMS98).

	Type of Structure	A	B	C	D	E	F
MASONRY	rubble stone, fieldstone	○					
	adobe (earth brick)	●	—				
	simple stone	···	●				
	massive stone		—	○	···		
	unreinforced, with manufactured stone units	···	●	···			
	unreinforced, with RC floors		—	●	···		
	reinforced or confined			···	●	—	

(Kosugi Lab., 2004). The research group of Tokyo Tech. Univ. and Asia Air Survey kindly provided us with the images, and GIS-based street and housing maps, as shown in Figs. 4, 6, and 7. In addition, they provided us with change detection maps before and after the earthquake (Kosugi Lab., 2004), which were very useful to find damaged areas during the investigation.

Table 2 and Fig. 5 show the total numbers of buildings investigated, and the damage grades for each building type. From Fig. 5 (a), more than half of the buildings are simple masonry, and about 20% are adobe and the masonry with steel frames. There are few masonry with RC frame and moment frame buildings. From Fig. 5 (b), most of the adobe buildings were completely destroyed (Grade 5), and the ratios of Grades 5 and 4 accordingly decrease with higher vulnerability classes, that is, from adobe (vulnerability class A) and simple masonry (class B) to masonry with steel and RC frames (class C and D). Even though the numbers are not large, it is evident that engineering buildings (steel and RC moment

Table 2. The aftershock stations and the number of the buildings investigated around the stations.
(A : adobe, M : simple masonry, MS : masonry w. steel, MRC : masonry w. RC, S : steel frame, RC : RC frame).

Station No.	City Name	Longitude	Latitude	A	M	MS	MRC	S	RC	Total
1	Bam	29.112	58.367	16	30	3	1	1	0	51
2	Bam	29.106	58.358	94	73	101	1	11	1	281
3	Bam	29.107	58.324	0	82	11	3	0	1	97
4	Bam	29.108	58.343	14	31	7	1	1	0	54
5	Bam	29.098	58.374	9	50	16	1	3	1	80
6	Bam	29.080	58.353	0	48	5	12	6	0	71
7	Bam	29.095	58.355	24	33	29	1	5	1	93
8	Baravat	29.070	58.404	12	93	5	0	1	1	112
			Total	169	440	177	20	28	5	839

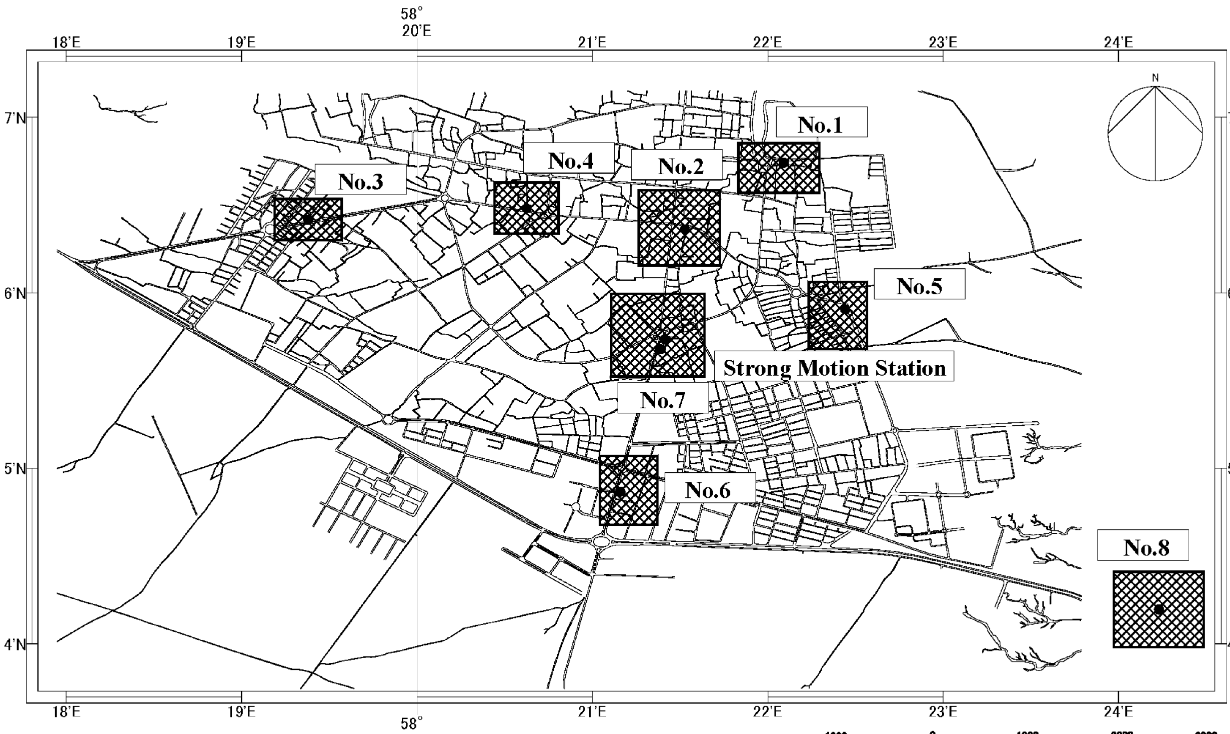
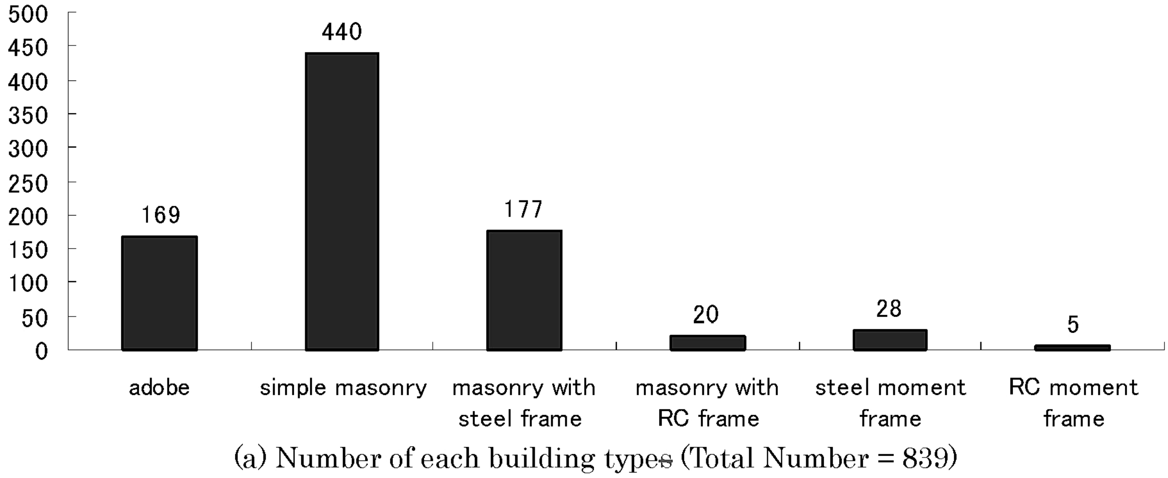
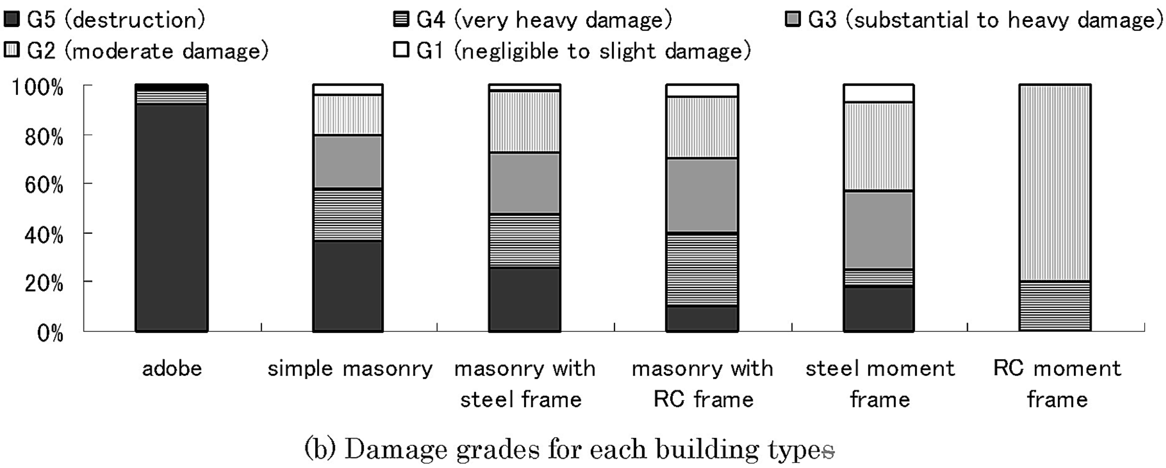


Fig. 4. Map of Bam city and the eight investigated areas (drawn from satellite image ; Kosugi, Lab., 2004).



(a) Number of each building type (Total Number=839).



(a) Number of each building type (Total Number=839).

Fig. 5. Total numbers and damage grades of investigated buildings.

frame) suffered little damage compared to non-engineering buildings.

3. 3 Building Damage and Estimation of Seismic Intensity in Each Area

Next, we discuss damage in more detail around the 8 stations, and evaluate their EMS98 intensities. Table 3 shows relations among vulnerability classes, damage grades, and intensities.

Figure 6 (a) shows a table and a map of buildings investigated around station 1. This station is located at the northeast side of Bam city south of Arge Bam (see Figs. 2 and 4). Houses in this area seemed to be old. All of the adobe houses (Class A) were destroyed (Grade 5), which indicates the EMS98 intensity is more than X from Table 3. More than half of the simple masonry buildings (Class B) are also Grade 5, which suggests the intensity may approach XI. Numbers of other types of building are insufficient to estimate intensity. Thus, we estimate MSK intensity in this area as X to XI.

Figure 6 (b) shows a table and a map of buildings investigated around station 2. This area is located in the old city of Bam, including the main streets. Thus, many of the buildings are old commercial buildings, which are mostly masonry with steel frame. Almost all of the adobe houses (Class A) were completely destroyed (Grade 5), suggesting EMS98 intensity of more than X. Many simple masonry buildings (Class B) and masonry buildings with steel frames (Class C) are Grade 5, and most of the simple masonry build-

Table 3. EMS98 intensity scale using damage grade and vulnerability class.

Vulnerability Class	Damage Grade	a few (0–20%)	many (20–60%)	most (60–100%)
A adobe	G5	VIII	IX	X
	G4	VII	VIII	
	G3		VII	
	G2	VI		
	G1	V	VI	
B simple masonry	G5	IX	X	XI
	G4	VIII	IX	
	G3	VII	VIII	
	G2	VI	VII	
	G1	V	VI	
C masonry with steel frame	G5	X	XI	XII
	G4	IX	X	XI
	G3	VIII	IX	
	G2	VII	VIII	
	G1	VI		
D masonry with RC frame	G5	XI		XII
	G4	X	XI	
	G3	IX	X	
	G2	VIII	IX	
	G1	VII		

ings with steel frames are more than Grade 4, which suggests that the intensity might approach XI. Therefore, we estimate MSK intensity in this area as X to XI.

Figure 6 (c) shows a table and a map of buildings investigated around station 3. This station is located in a western suburb of Bam city, and the houses in the area are relatively new. Thus, there are no adobe houses. Even though we classify most houses as simple masonry, as shown in the table, it was not easy to judge them only from appearances, because most had minor damage. Thus, some may have steel or RC reinforcements. From the table, a few simple masonries (Class B) are Grades 5 and 4, and many are Grades 3 and 2, which suggests intensity may be VII to IX. A few masonry with steel frame buildings (Class C) are Grades 4 and 3, and many are Grade 2, which suggests the intensity may be VIII to IX. Thus, we estimate MSK intensity as VIII to IX.

Figure 6 (d) shows a table and a map of buildings investigated around the station 4. This area is between stations 2 and 3, and the houses are relatively old. All of the adobe houses (Class A) are Grade 5, suggesting an intensity of more than X. Many simple masonry buildings (Class B) are Grades 4 and 5, which also indicates the intensity may be IX to X. In addition, most of masonry with steel frame buildings (Class C) are Grade 3. Therefore, the MSK intensity in this area is estimated to be around X.

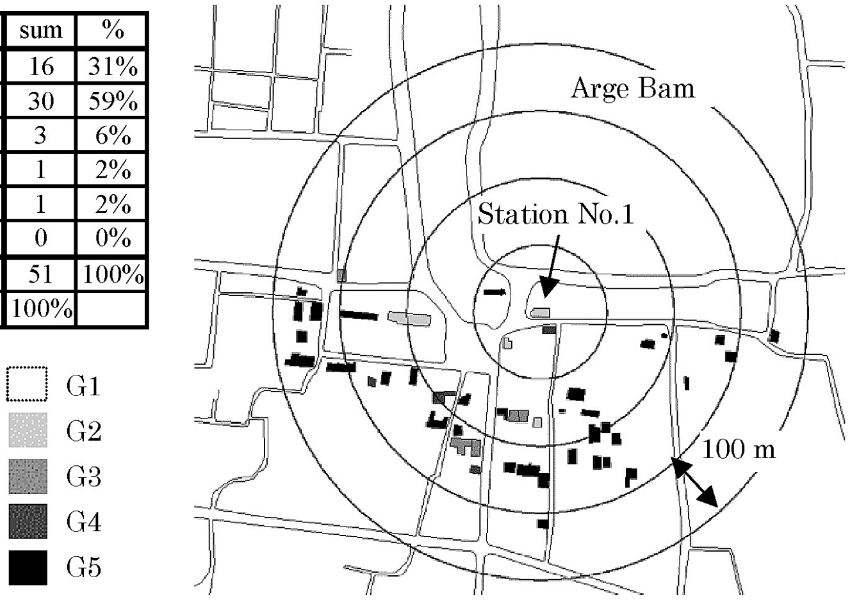
Figure 6 (e) shows a table and a map of buildings investigated around station 5. This area is located at the east end of Bam city close to the Bam fault, and the houses are relatively old. Almost all of the adobe houses (Class A) are Grade 5, suggesting an intensity of more than X. Most are simple masonry (Class B) and many masonry with steel frame buildings (Class C) are Grade 5, which suggests the intensity might approach XI. Therefore, the MSK intensity in this area is estimated to be X to XI.

Figure 6 (f) shows a table and a map of buildings investigated around station 6. This station is located south of Bam city, and the houses are relatively new, with no adobe houses. Many simple masonry buildings (Class B) are from Grade 3 to 5, which suggests the intensity might be VIII to X. Many masonry with RC frame buildings (Class D) are Grades 4 and 3, which suggests the intensity might be X to XI. Even though the number of buildings is not large, most steel frame houses (Class D to E) are Grade 2, which suggests the intensity might be around X. Consequently, we estimate MSK intensity in this area to be around X.

Figure 6 (g) shows a table and a map of buildings investigated around the station 7. This station is located near the center of Bam city, where the strong motion station is located. This area includes main streets, and their commercial buildings seemed to be relatively new, and the residential houses seemed relatively expensive and well constructed. Most adobe houses (Class A) are Grade 5, suggesting intensity is more than X. Many simple masonry buildings (Class B) are Grades 3 to 5, which also suggests the intensity may be VIII to X. Many masonry with steel frame buildings (Class C) are Grade 3, and a few of them are Grade 4, which also suggests the intensity might be IX. Therefore, we estimate MSK intensity in this area to be IX to X.

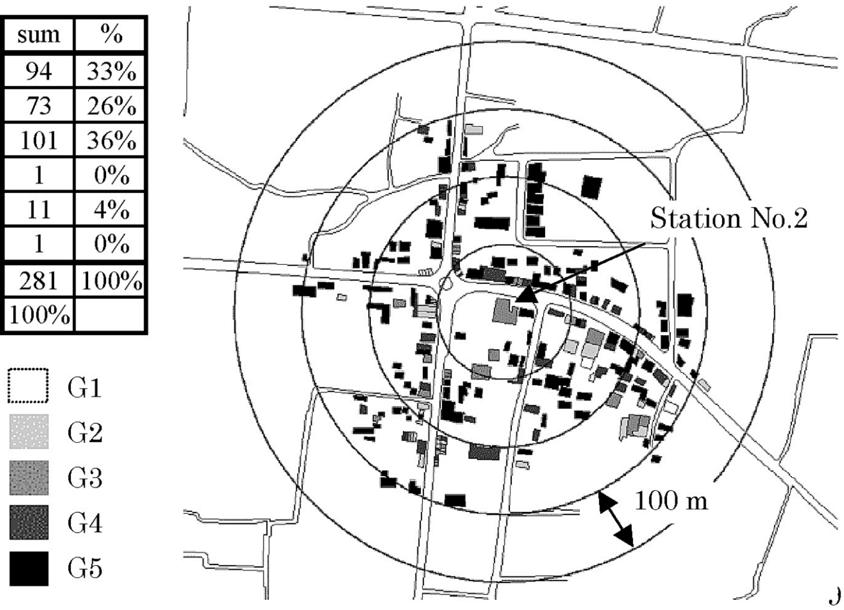
Figure 6 (h) shows a table of buildings investigated around station 8. A street map is not available, because this station is located in Baravat City, east of

No.1	G5	G4	G3	G2	G1	sum	%
A	16	0	0	0	0	16	31%
M	19	4	4	3	0	30	59%
MS	2	0	1	0	0	3	6%
MRC	0	0	1	0	0	1	2%
S	0	0	1	0	0	1	2%
RC	0	0	0	0	0	0	0%
sum	37	4	7	3	0	51	100%
%	73%	8%	14%	6%	0%	100%	



(a) Station No.1
(Intensity X to X I)

No.2	G5	G4	G3	G2	G1	sum	%
A	91	3	0	0	0	94	33%
M	33	20	8	9	3	73	26%
MS	32	31	13	23	2	101	36%
MRC	0	0	0	1	0	1	0%
S	2	1	5	3	0	11	4%
RC	0	1	0	0	0	1	0%
sum	158	56	26	36	5	281	100%
%	56%	20%	9%	13%	2%	100%	



(b) Station No.2
(Intensity X to X I)

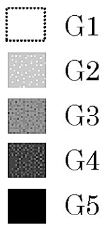
Fig. 6. Tables and maps of investigated buildings around the eight stations.
A : adobe, M : simple masonry, MS : masonry w. steel, MRC : masonry w. RC, S : steel frame, RC : RC frame.

Bam city. The buildings in this area seemed to be relatively old. Even though the number of adobe houses (Class A) is not large, many are Grades 4 and 5, suggesting intensity is around IX. Many simple masonry buildings (Class B) are Grades 4 to 5, which suggests the intensity may be IX to X. Thus, the MSK intensity in this area is estimated to be IX to X.

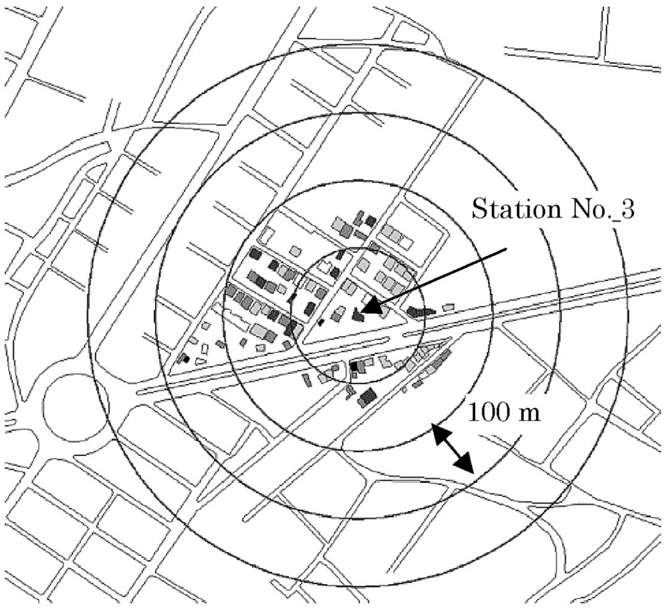
4. Conclusions

Figure 7 shows the rates of buildings with more than very heavy damage (Grades 4 and 5), and the estimated MSK intensities in the 8 areas, together with the damage map, which was estimated from aerial photos independently (National Cartographic Center of Iran, 2003). The comparison of damage ratios between our results and the damage map shows excellent agreement ; the north and east sides of Bam city, whose buildings are relatively old, show very high damage rates, whereas the south and west sides, whose buildings are newer, show much lower rates. Combining these damage rates and vulnerability classes of building types, we estimate the MSK

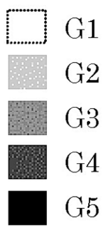
No.3	G5	G4	G3	G2	G1	sum	%
A	0	0	0	0	0	0	0%
M	3	12	26	33	8	82	85%
MS	0	2	1	7	1	11	11%
MRC	0	0	2	0	1	3	3%
S	0	0	0	0	0	0	0%
RC	0	0	0	1	0	1	1%
sum	3	14	29	41	10	97	100%
%	3%	14%	30%	42%	10%	100%	



(c) Station No._3
(Intensity VIII to IX)



No.4	G5	G4	G3	G2	G1	sum	%
A	14	0	0	0	0	14	26%
M	12	7	5	7	0	31	57%
MS	2	0	5	0	0	7	13%
MRC	0	0	0	1	0	1	2%
S	0	0	1	0	0	1	2%
RC	0	0	0	0	0	0	0%
sum	28	7	11	8	0	54	100%
%	52%	13%	20%	15%	0%	100%	



(d) Station No._4
(Intensity X)

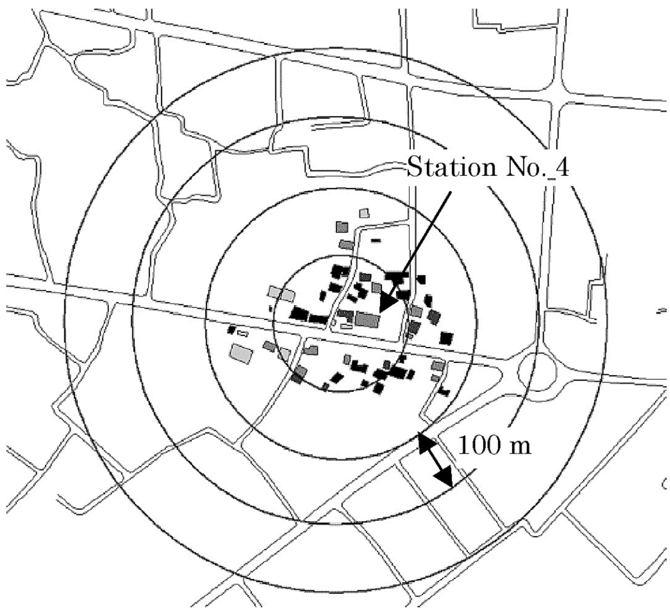


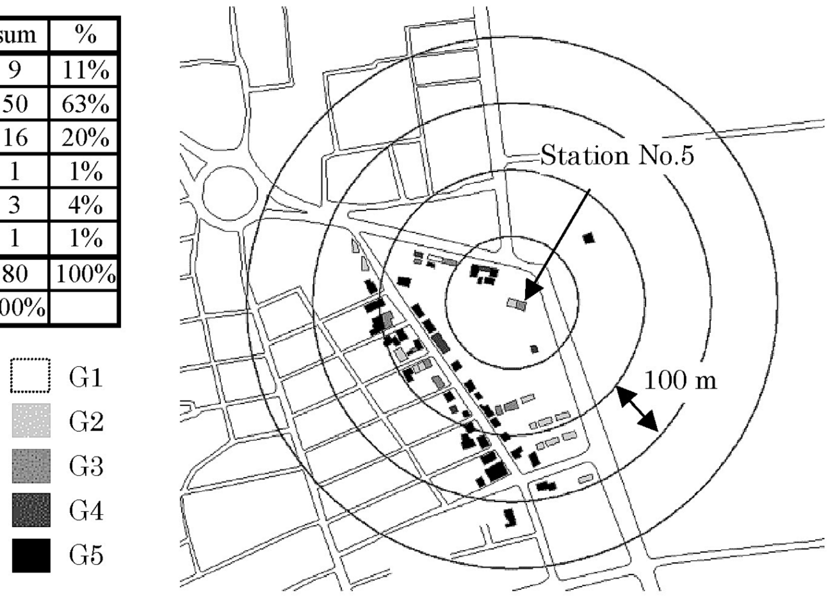
Fig. 6. (Continued)

intensity to be higher, X to XI, at the north and east sides, and to be lower, VIII to X, at the south and west sides. An independent study shows the MSK intensities in a wider area in and around Bam City are VIII to IX[2], which also validates our estimates. In future studies, we plan to construct vulnerability curves of various building types, by combining our results and the strong ground motions, which may be simulated using aftershock records on the basis of Green's empirical function methods.

Acknowledgements

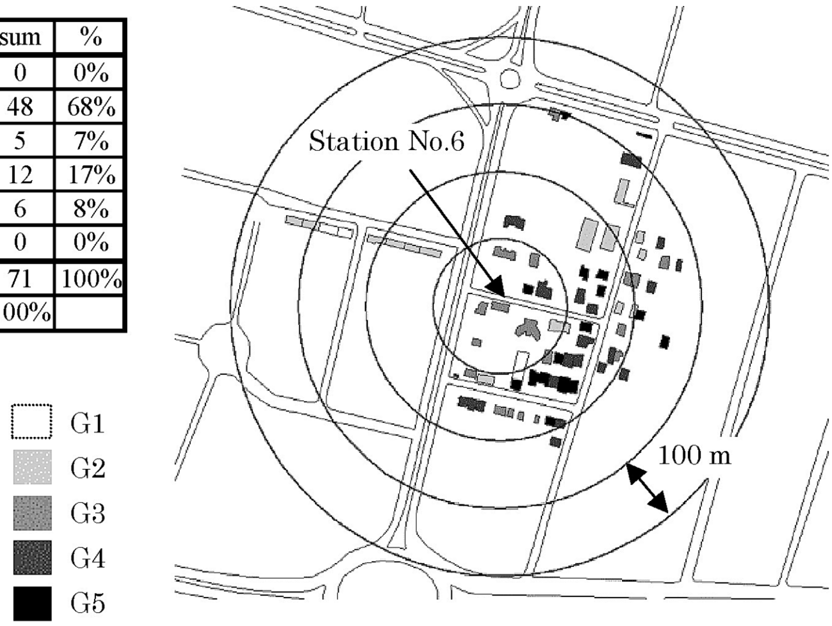
We thank Mr. G. Reza Nouri and Masud M. Ahari of IIEES for their help during the investigation. This research was carried out with a grand-in aid for scientific research from Monbu-Kagaku-sho (Japanese Ministry of Education, Culture, Sports, Science and Technology), Architectural Institute of Japan, and Japan Association for Earthquake Engineering (JAEE), in collaboration with IIEES (International Institute of Earthquake Engineering and Seismology) of Iran. The research group of the Kosugi Lab.

No.5	G5	G4	G3	G2	G1	sum	%
A	8	1	0	0	0	9	11%
M	31	2	6	10	1	50	63%
MS	9	2	2	3	0	16	20%
MRC	1	0	0	0	0	1	1%
S	2	0	1	0	0	3	4%
RC	0	0	0	1	0	1	1%
sum	51	5	9	14	1	80	100%
%	64%	6%	11%	18%	1%	100%	



(e) Station No.5
(Intensity X to X I)

No.6	G5	G4	G3	G2	G1	sum	%
A	0	0	0	0	0	0	0%
M	14	12	13	7	2	48	68%
MS	1	1	2	1	0	5	7%
MRC	1	6	3	2	0	12	17%
S	0	0	0	5	1	6	8%
RC	0	0	0	0	0	0	0%
sum	16	19	18	15	3	71	100%
%	23%	27%	25%	21%	4%	100%	



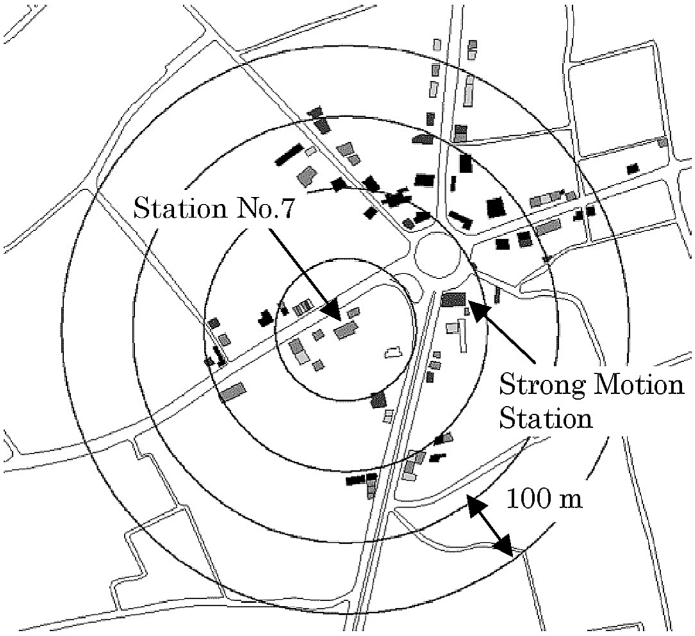
(f) Station No._6
(Intensity X)

Fig. 6. (Continued)

No.7	G5	G4	G3	G2	G1	sum	%
A	21	3	0	0	0	24	26%
M	6	10	15	1	1	33	35%
MS	0	2	16	11	0	29	31%
MRC	0	0	0	1	0	1	1%
S	1	1	1	1	1	5	5%
RC	0	0	0	1	0	1	1%
sum	28	16	32	15	2	93	100%
%	30%	17%	34%	16%	2%	100%	

(g) Station No.7
(Intensity Ⅸ to Ⅹ)

G1
G2
G3
G4
G5



No.8	G5	G4	G3	G2	G1	sum	%
A	6	4	1	1	0	12	11%
M	44	27	16	5	1	93	83%
MS	0	1	3	0	1	5	4%
MRC	0	0	0	0	0	0	0%
S	0	0	0	1	0	1	1%
RC	0	0	0	1	0	1	1%
sum	50	32	20	8	2	112	100%
%	45%	29%	18%	7%	2%	100%	

(h) Station No.8
(Map is not available
Intensity Ⅸ to Ⅹ)

Fig. 6. (Continued)

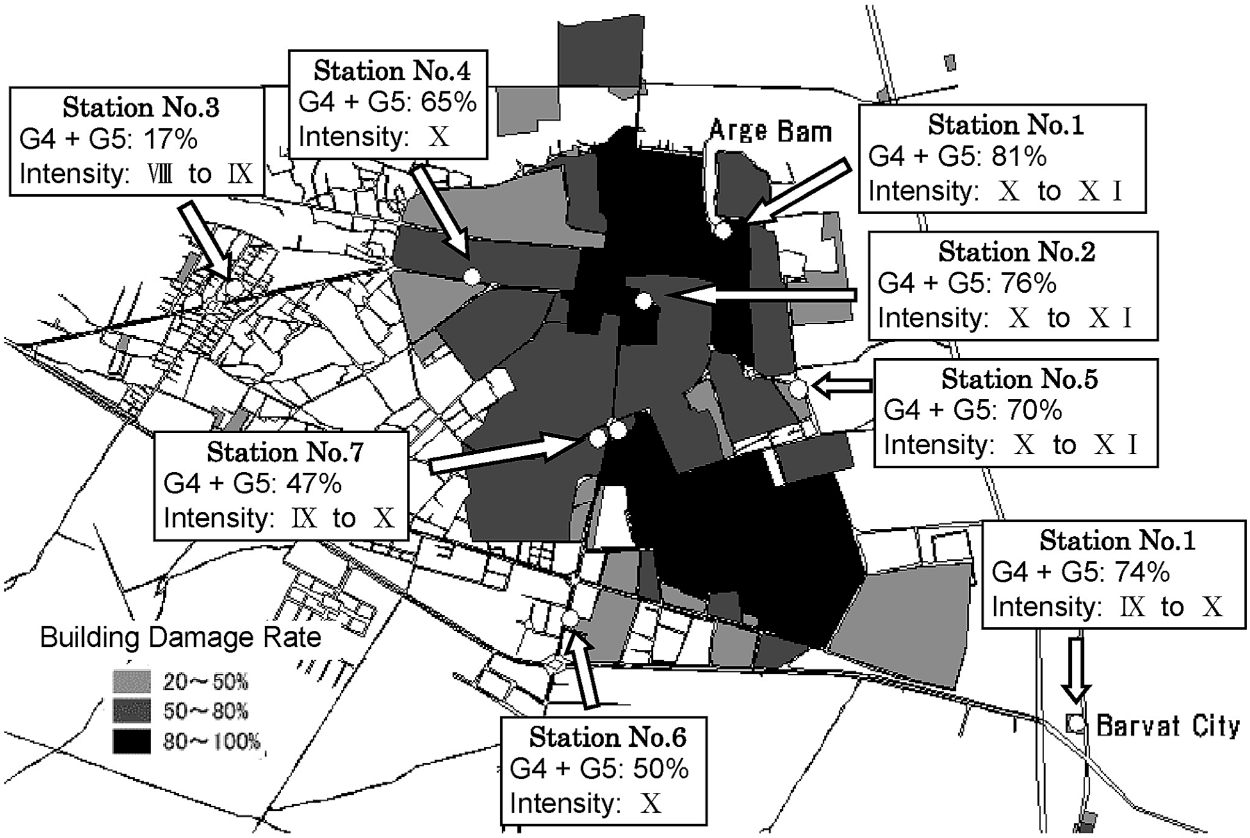


Fig. 7. Damage rates and estimated MSK intensities, together with damage map estimated from aerial photos independently[4].

of Tokyo Tech. Univ. and Asia Air Survey kindly provided us satellite images of Quick Bird, and the GIS-based street and housing maps. We used the strong ground motion records in Bam City under the research contract between BHRC (Building And Housing Research Center) and the JAEE team.

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