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STATISTICAL EVALUATION OF EMBEDMENT EFFECT ON DAMAGE TO BUILDING STRUCTURES BASED ON DATA FROM THE 1995 HYOGOKEN-NANBU EARTHQUAKE

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ABSTRACT: In the 1995 Hyogoken-Nanbu Earthquake, a lot of building structures were severely damaged, and valuable data was compiled after the investigation by the Architectural Institute of Japan (AIJ). This study statistically evaluates effect of embedment due to presence of basements on damage mitigation of reinforced concrete (RC) building structures based on building damage data from the 1995 Hyogoken-Nanbu Earthquake. A multivariate analysis (Hayashi's Quantification II) is used to investigate factors (items) that have a strong effect on the degree of damage to RC buildings. The results indicate that embedment has a remarkable effect on reducing damage; the degree of which is similar to the construction year effect (due to major revision of Japanese building standard law that became effective in 1981). This finding may support further positive adoption of embedment effect in seismic design practice.

Keywords: Embedment, Hyogoken-Nanbu Earthquake, SSI, Building Structure

1. INTRODUCTION

Variation of earthquake motions from free-field to foundation is caused by differences of stiffness and mass of the foundation from the soil. Soil-structure interaction (SSI) associated with the difference in stiffness is regarded as kinematic soil-structure interaction, which is conveniently represented by the transfer function in the frequency domain as the ratio of massless foundation motion to free-field surface ground motion.

Transfer functions for an embedded cylinder were theoretically calculated by Elsabee et al. [1] for soil resting on rock, and by Day [2] for halfspace soil. Their theoretical works indicate that embedment has a marked influence on kinematic soil-structure interaction.

However, it was not until quite recently that the effect was incorporated into the building design guideline of the Architectural Institute of Japan (AIJ) [3]. Hence, buildings constructed before the 1995 Hyogoken-Nanbu Earthquake might have some amount of extra strength, assuming that kinematic SSI effect was not taken into account in their design, and this fact may have resulted in reducing damage to such buildings.

In this study, effect of embedment due to the presence of basement on damage reduction of building structures is statistically investigated by using a multivariate analysis based on the damage database of RC and SRC public building structures during the 1995 Hyogoken-Nanbu Earthquake.

2. DATABASE

2.1 Database of Damage to RC Buildings

The AIJ carried out investigations into damage to RC and SRC building structures during the 1995 Hyogoken-Nanbu Earthquake, and the data was compiled into a report published in 1997 [4]. The dataset includes construction year, number of stories (story stands for number of floors above the ground) and number of basement stories, for both damaged and undamaged buildings. This study utilizes the data of public building structures that have an adequate number of both embedded and non-embedded structures to investigate the effect of embedment. As a representative index of expressing strong ground motion, peak ground velocity (PGV) distribution in the Kobe area evaluated by Hayashi et al. [5] was added by the author to the database. Discarding some data collected from obviously liquefied area (such as Port Island), 72 sets of building data were extracted for the analysis from the original database as shown in Table 1. The area where damaged building data were extracted is shown on in Fig.1 together with area where seismic intensity was 7 (strongest) on the JMA scale. The damaged building data were mostly from Kobe city but they include 2 from Itami city (shown as ITM), 5 from Ashiya city (ASY), 2 from Takarazuka city (TKR), 4 from Amagasaki (AMG) and 5 from Nishinomiya city (NSN). Damage to building structures is classified into 6 levels (from level 1 to level 6) as shown in Table 2. Missing data from the original database was gathered by telephone inquiry by the author.

Table 1 Database used for the analysis (data was taken from refs. [4],[5])

No.	Damage level	Construction year	No. of stories above ground	No. of basement stories	PGV(cm/s)
1	4	1992	8	1	120-140
2	2	1980	9	2	-50
3	4	1980	10	1	-50
4	3	1993	10	2	50-80
5	5	1964	7	2	120-140
6	6	1957	8	1	120-140
7	4	1977	8	1	140-
8	3	1993	7	2	140-
9	2	1991	8	1	140-
10	1	1975	3	2	-50
11	5	1975	12	0	140-
12	2	1987	3	1	120-140
13	2	1991	8	0	50-80
14	1	1979	8	1	-50
15	3	1966	9	2	-50
16	1	1988	6	1	-50
17	5	1971	8	3	120-140
18	2	1972	7	2	-50
19	1	1990	4	3	120-140
20	3	1972	4	1	120-140
21	2	1985	3	1	-50
22	2	1992	10	1	-50
23	3	1964	13	2	-50
24	3	1970	3	2	-50
25	3	1958	5	2	-50
26	4	1965	5	1	120-140
27	3	1977	11	0	90-110
28	3	1973	9	2	50-80
29	2	1970	13	2	90-110
30	2	1990	14	4	90-110
31	3	1966	13	2	90-110
32	4	1981	9	3	-50
33	3	1972	8	3	50-80
34	3	1981	5	2	90-110
35	4	1965	6	1	120-140
36	3	1967	4	1	120-140
37	5	1967	9	1	50-50
38	4	1954	6	0	-50
39	3	1964	6	1	50-80
40	4	1974	9	2	140-
41	3	1968	6	1	140-
42	2	1965	4	0	140-
43	5	1964	9	2	120-140
44	2	1990	9	3	50-80
45	2	1980	5	0	90-110
46	3	1968	6	2	-50
47	4	1973	8	1	-50
48	4	1986	8	1	90-110
49	4	1975	3	0	120-140
50	3	1981	6	1	-50

Table 1(cont'd) Database used for the analysis (data was taken from refs. [4],[5])

No.	Damage level	Construction year	No. of stories	No. of basement stories	PGV(cm/s)
51	2	1985	6	1	50-80
52	2	1982	9	2	50-80
53	2	1986	7	1	120-140
54	4	1967	5	1	50-80
55	3	1980	13	0	120-140
56	3	1977	5	1	120-140
57	3	1992	7	0	120-140
58	4	1933	3	1	120-140
59	4	1971	4	0	120-140
60	4	1976	3	1	120-140
61	4	1990	2	0	120-140
62	4	1959	4	1	50-80
63	4	1961	4	1	90-110
64	4	1967	6	1	140-
65	5	1958	2	0	-50
66	6	1976	7	1	120-140
67	5	1972	2	0	140-
68	4	1921	2	1	50-80
69	4	1964	3	0	50-80
70	4	1969	5	0	90-110
71	4	1992	2	1	140-
72	4	1987	2	0	140-

2.2 Effect of Japanese Building Standard Law Effective in 1981

Major revision was made to the Japanese Building standard law effective in 1981, thus, it is recognized that construction year is the key factor that influences the degree of damage to building structures. Fig.2 compares the ratio of each damage level of buildings constructed before 1981 and after 1982. For buildings constructed before 1981, the most outstanding damage levels are level 3(minor) and level 4(medium). Whereas for buildings constructed after 1982, level 2(slight damage) occupies about the half of the total damage, and the percentage of level 3 to level 6 in the total is much smaller compared with Fig.2(a). It is obvious that buildings constructed after 1982 show less degree of damage level compared with those constructed before 1981. This is due to the major revision of Japanese building standard law in which seismic safety of buildings are ensured by two step examination (1) allowable stress design method for medium earthquakes and (2) ultimate seismic safety for major earthquakes.

Since Kansai area including Kobe areas is not earthquake-prone area, there was no such earthquake that caused structural effect (some amount of damage) on the buildings included in the database prior to the 1995 Hyogoken-Nanbu Earthquake. Some old buildings in the database (No.58, 68) has experienced 1946 Showa-Nankai Earthquake and 1948 Fukui Earthquake, however, shaking level was middle as epicenters are far enough (approximately 200km away) from Kobe area. Hence, it is assumed that only Kobe earthquake caused structural damage to those buildings included in the database.

3. STATISTICAL EVALUATION OF EMBEDMENT EFFECT BY MULTIVARIATE ANALYSIS

3.1 Method

Effect of embedment on damage reduction of buildings is examined using a multivariate analysis. The problem to be solved in this study is to ascertain factors (items) that have strong influence on the degree of damage to buildings, especially paying attention to the embedment effect. Hayashi's Quantification II [6] is utilized in this study. This method is basically a multivariate discrimination analysis, however, it can deal with a discrimination problem even when variables are given as qualitative data (such as

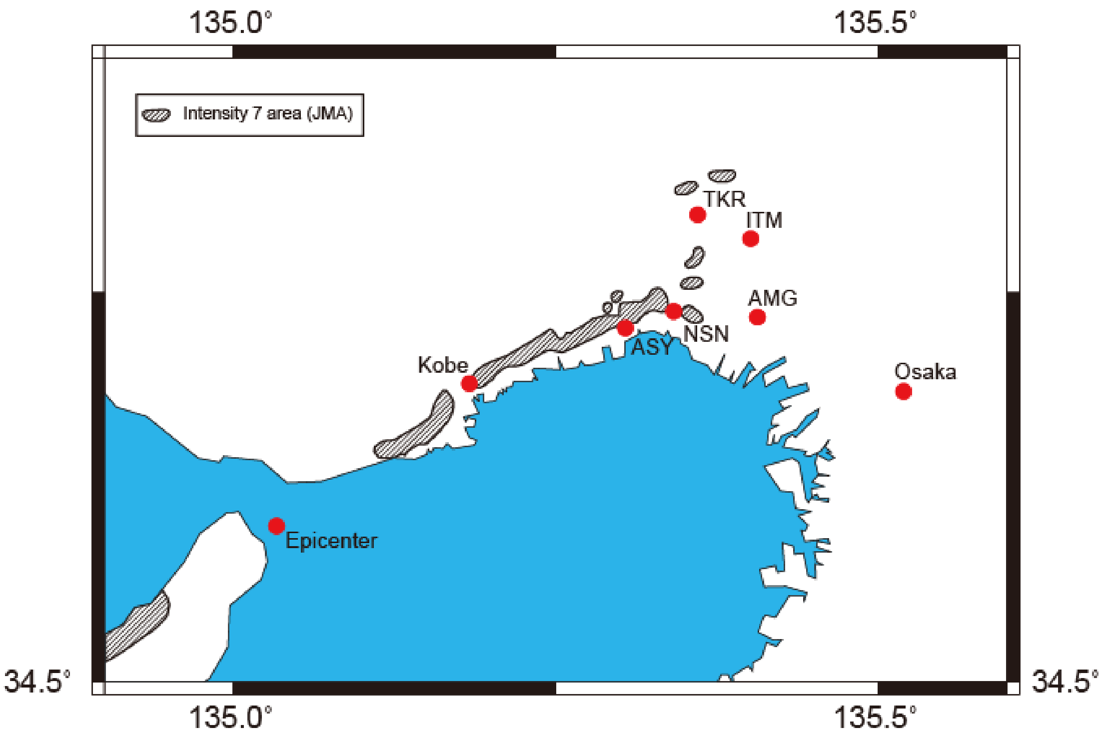


Fig.1 Map of area where damaged buildings data were extracted

Table 2 Damage levels

Damage level	Description
Level 1	No damage
Level 2	Slight damage
Level 3	Minor damage
Level 4	Medium damage
Level 5	Serious damage
Level 6	Collapse

classification of construction years) by incorporating 0-1 dummy variables. The method is so well known in Japan that some computer program packages include Hayashi's quantification.

Referring Tanaka et al[7], a brief explanation of the method is given below. For more details, please refer this book.

Suppose that there are *K* outside criteria (response variables), *R* items (each item has c_R categories). To deal with qualitative data, 0-1 dummy variables are introduced. $\delta_{i\alpha}$ becomes 1 only when a sample (α-th sample of i-th group) fall into a sub-category of each item (*k* category of *j* item).

$$\delta_{i\alpha}(jk) = \begin{cases} 1 \\ 0 \end{cases} \quad (1)$$

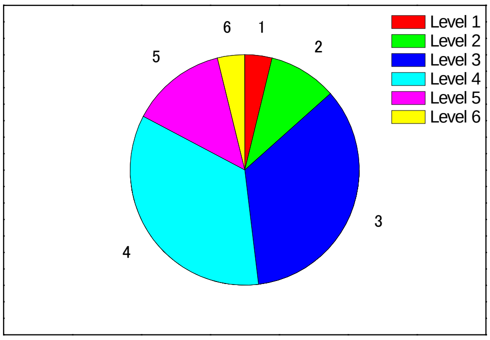
To discriminate individuals into several groups, sample scores are computed using the following linear equation.

$$Y_{i\alpha} = \sum_{j=1}^{R}\sum_{k=1}^{c_j} a_{jk}\delta_{i\alpha}(jk) \quad (2)$$

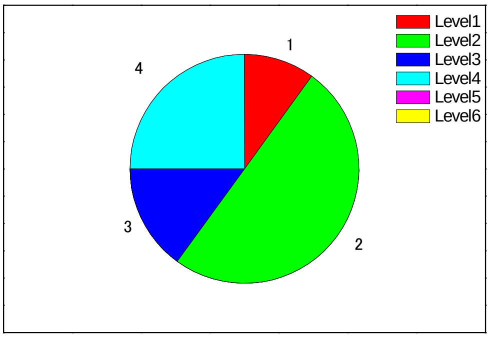
where a_{jk} is unknown coefficients. As already known in the analysis of variance, total sum of squared differences between scores on $Y_{i\alpha}$ and the grand mean is partitioned into sum of squared differences between group means and the grand mean (between group variability), and sum of squared difference between individual scores and their respective groups means (within-group variability).

$$\sum_{i=1}^{K}\sum_{\alpha=1}^{n_i}(Y_{i\alpha}-\bar{Y})^2 = \sum_{i=1}^{K} n_i(\bar{Y}_i-\bar{Y})^2 + \sum_{i=1}^{K}\sum_{\alpha=1}^{n_i}(Y_{i\alpha}-\bar{Y}_i)^2 \quad (3)$$

where $\bar{Y}$ and $\bar{Y}_i$ are mean values of total sample scores (grand mean) and samples' scores within subgroups. Correlation ratio is calculated using the following equation as the ratio the sum of squared differences between group means and the grand mean to total sum of squared differences between groups' means and the grand mean. Unknown coefficients a_{jk} are determined so that the correlation ratio becomes the maximum.



(a) Before 1981



(b) After 1982

Fig.2 Effect of construction year on damage ratio of buildings

$$\eta^2 = \frac{\sum_{i=1}^{K} n_i (\bar{Y}_i - \bar{Y})^2}{\sum_{i=1}^{K} \sum_{\alpha=1}^{n_i} (Y_{i\alpha} - \bar{Y})^2} \to \max \qquad (4)$$

Implementing some mathematical manipulation, the problem attributes to generalized eigenvalue problem.

3.2 Categories for the Quantification II

The original datasets were re-categorized for the analysis by quantification II as shown in Table 3. Dummy variables were, then, introduced based on the new category to quantify the qualitative data.

Cross-tabulation table is shown in Table 4. It is important for the Quantification II to adjust the number of samples falling into each category of items. Hence, attention was paid to the aforementioned re-categorizing of the dataset.

3.3 Computational Results

Results calculated by quantification II are shown in Table 5. Looking at the category scores of the outside variable (damage level), it is recognized that higher damage level has a lower category score. Hence, category scores of each item have an inverse relationship (i.e. a larger score contributes to less damage). From the values of range and the partial correlation coefficient, it is apparent that items of construction year and presence of adequate basements have about the same value as is also shown in Fig. 3. This indicates that these items have an influence on damage to the same degree. Paying attention to the category scores of each item shown in Table 5 and Fig.4, we can understand that buildings that have two or more basement levels show less degree of damage; the degree of which is similar to the construction year effect due to major revision of Japanese building standard law which became effective in 1981. Thus, these categories contribute to lessening damage to building structures.

Table 3 Re-categorization of each item for the statistical analysis

Item	Description	Category
Construction years	before 1971	1
	1972-1981	2
	after 1982	3
Stories above ground	1 ～ 5	1
	6 or more	2
Basement stories	0	1
	B1	2
	B2 or more	3
PGV(cm/s)	less than 80	1
	90 or more	2
Damage level	Level 1～3	1
	Level 4～6	2

Table 4 Cross-tabulation table for variables

		Construction year			Stories above ground		No. of basement stories			PGV(cm/s)	
		-1971	1972-1981	1982-	1-5	6-	0	B1	B2 -	- 80	90 -
Construction year	-1971	29	0	0	14	15	6	13	10	13	16
	1972-1981	0	23	0	8	15	6	9	8	10	13
	1982-	0	0	20	6	14	4	10	6	8	12
Stories above ground	1-5	14	8	6	28	0	10	13	5	9	19
	6-	15	15	14	0	44	6	19	19	22	22
No. of basement stories	0	6	6	4	10	6	16	0	0	4	12
	B1	13	9	10	13	19	0	32	0	13	19
	B2 -	10	8	6	5	19	0	0	24	14	10
PGV(cm/s)	-80	13	10	8	9	22	4	13	14	31	0
	90 -	16	13	12	19	22	12	19	10	0	41

Table 5 Computational results

Item	Category	Number of items	Category score	Range	Partial Correlation Coefficient
Construction years	before 1971	29	-0.6630	1.5409	0.3426
	1972-1981	23	0.0725		
	after 1982	20	0.8779		
Stories above ground	1～5	28	-0.0293	0.0479	0.0130
	6～	44	0.0186		
No. of basement stories	0	16	-0.5180	1.4201	0.3359
	B1	32	-0.4176		
	B2 or more	24	0.9021		
PGV(cm/s)	less than 80	31	0.3918	0.6881	0.1911
	90 or more	41	-0.2963		
Damage level	Level 1-3	39	0.4629		
	Level 4-6	33	-0.5470		

Partial correlation coefficient = 0.2568

4. CONCLUSIONS

This study statistically investigated the effect of embedment due to presence of basement on damage mitigation of reinforced concrete building structures during the 1995 Hyogoken-Nanbu Earthquake. The results indicate that the effect of embedment has a remarkable influence on reducing damage to buildings when there exists sufficient embedment (two or more basement levels). The degree of reducing damage by embedment is similar to the effect of construction year due to the major revision of the Japanese building standard law in 1981. Although the results from this study may support more positive adoption of embedment effect in design practice in Japan, the following two points should be noted: (1) The number of data used in the analysis was only 72 which may not be enough. (2) The result reflects only a single earthquake event (1995 Hyogoken-Nanbu Earthquake). Therefore, verification of our findings using some other earthquakes and their damage data is necessary in the future.

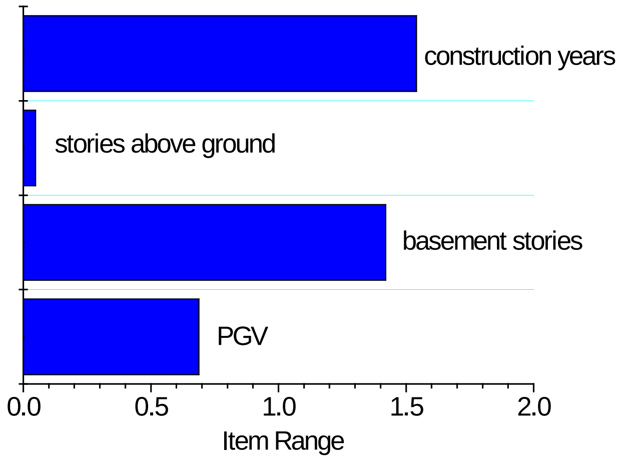


Fig.3 Item range

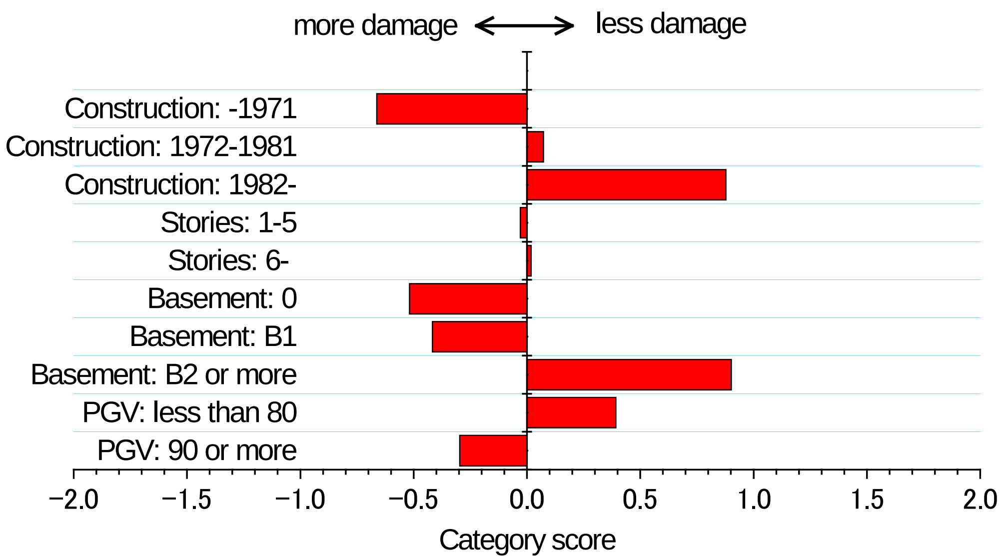


Fig.4 Category score

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