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SEISMIC URBAN FACTOR TO PREVENT SEVERE DAMAGE BY MAJOR EARTHQUAKE

Hiroyuki NAKAHARA[1] and Kazuo MATSUMURA[2]

SUMMARY

The occurrence of major earthquake near the area with high densely inhabited cities causes a lot of collapsed buildings and brings the several social problems to the area. Therefore, it is important to decrease the total amounts of damaged buildings within the allowable disaster level which is defined by social need of each country. The buildings in densely populated area should be required higher seismic performances rather than those in under-populated area in the quake-prone countries.

The two approaches which reduce the earthquake risk have been studied. The first approach is to propose the new design factor which restricts the total of damaged buildings in urban area. This is the seismic load factor according to the density of buildings and named as the seismic urban factor. The damage rate of the buildings is obtained probabilistically by using the vulnerability function of wooden houses and seismic hazard of ground motion in 500-year return period. Against to the seven model cities classified by the total number of existing houses, the factors are obtained by using the calculated damage rates. The general trend of relationships between the seismic urban factors and the densities of buildings is discussed.

The second approach is seismic improvement which reinforces the building to enhance the earthquake resistant performance. The effects of seismic improvements in one model city are estimated by the same probabilistic procedure as the first approach. The earthquake load is equal to the above distribution, but the distribution of the strength of buildings is referred to the results of seismic evaluations of RC buildings which have been conducted widely in Japan after the 1995 Hyogo-ken Nanbu Earthquake. The targets of seismic improvements for one model city are concretely calculated to make the amounts of damaged RC buildings half.

INTRODUCTION

One of the most serious problems of the earthquake disaster is the difficulty of the functional recovery in the damaged area, because the major earthquake often causes the extensive amount of collapsed buildings in a few seconds. If the amounts of damaged buildings exceed the allowable level corresponding to the economic, traffic situation and infrastructure, the problem is expanded from the each damaged building to

[1] Research Associate, Dept. of Architecture, Faculty of Engineering, Kagoshima University, Japan
[2] Prof., Dept. of Architecture, Faculty of Engineering, Kagoshima University, Japan

the damage of the social activity. The disaster level of one city is depend on not only the magnitude of the earthquake but also the total number of existing buildings in the focal region. For example, the M7.2 Hyogo-ken Nanbu Earthquake occurred in 1995 in Japan caused the 6,432 dead and over 240,000 collapsed buildings. On the other hand, there were no loss of human life and only 539 collapsed buildings by the M7.3 Tottori-ken Seibu Earthquake in 2000. The velocity response spectra with 2% damping ratio of these two earthquakes are shown in Figure 1.

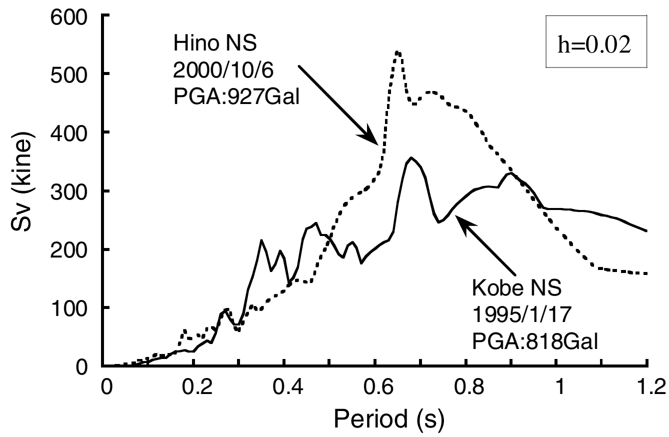


Figure 1 Velocity response spectra with 2% damping ratio

The solid line shows the Hyogo-ken Nanbu Earthquake (Kobe NS, 1995/1/17) and the dotted line shows the Tottori-ken Seibu Earthquake (Hino NS, 2000/10/6), the peak ground accelerations of them were 818 Gal and 927 Gal, respectively. From the comparison of the two spectra, the difference is not so clearly observed. The hypocenters of the two earthquakes were shallow within 20 km deep and were not located at the ocean bottom trench but located at near the land. These earthquakes had very similar characters but the disaster levels were quite different.

The main reason for the difference of the disasters is due to the total number of existing buildings in the damaged area. From the investigation conducted in 2000 by the Statistical Information Institute for Consultant and Analysis of Japan [1], the amounts of buildings of Kobe City and Nishinomiya City which are located within 40 km from the epicenter of the Hyogo-ken Nanbu Earthquake are about 550,000 and 150,000. Osaka City is biggest city in the west part of Japan and has 1,100,000 buildings. The location of Kobe City is near Osaka City and these cities face the Pacific Ocean. On the other hand, there is no big city which is located within 50 km from the epicenter of the Tottori-ken Seibu Earthquake. Yonago City is the nearest city from the epicenter, where the amounts of buildings are 47,000. Sakaiminato City located at 60 km apart has only 12,000 buildings. These cities are located the coast of the Japan Sea where the density of population is relatively low.

Therefore, it is necessary to control the seismic performance levels corresponding to the densities of buildings. The two approaches which reduce earthquake risk have been studied. One is to propose the new design factor which restricts the total of damaged buildings in urban area. This is defined as seismic urban factor which is available for constructing new wooden houses in crowded area. The other is to show the rational target of seismic improvement by using the results of the seismic evaluations conducted at the real prefecture in Japan.

SEISMIC HAZARD IN JAPAN

In order to control the number of damaged buildings at any area in Japan, it is necessary to investigate the seismic hazard level in the each area. In this study, the seismic hazard of the maximum velocity of ground motion in 500-year return period is used to predict the seismic risk. The values of the seismic hazard are referred to the results of the investigations conducted by co-author, Matsumura [2]. His proposed hazard map is shown in Figure 2. On the bases of the velocity of about 30 cm/s which is the mean value of all cities in Japan, two higher risk areas and two lower risk areas are set to make five levels of seismic hazard as shown in the figure. The areas of highest risk level are located along the coast of the Pacific Ocean. The velocity of the highest hazard level is calculated about 2.8 times larger than that of the lowest area.

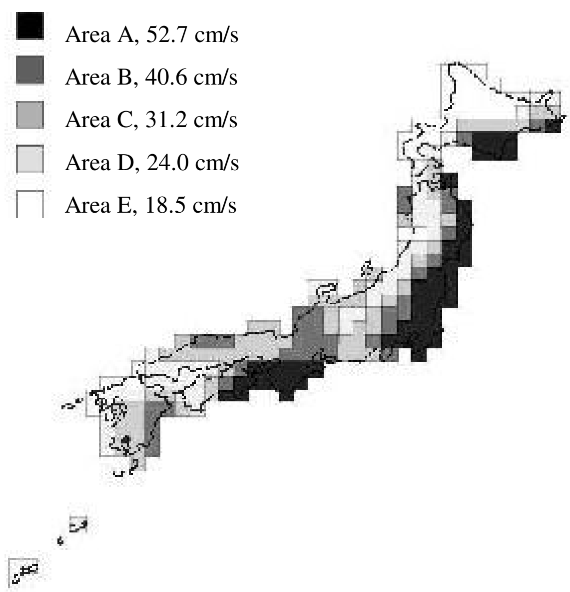


Figure 2 Seismic hazard of the maximum velocity of ground motion in 500-year return period

Using the five levels of ground motions, the rates of damaged buildings and proposed new design factors which restrict the total of damaged buildings are discussed hereafter, in the section of SESMIC URBAN FACTOR.

DAMAGE RATE OF WOODEN HOUSES

If the distribution of strength of buildings in one city is known, the probabilistic method can be adopted to predicted the rate of damaged buildings. The equation to calculate the damage rate $P_f(v)$ of wooden houses was proposed by Hasegawa et al. [3] from the statistical study of damaged detached-houses by the 1995 Hyogo-ken Nanbu Earthquake. The damage rate is calculated by the equation (1) as follows;

$$P_f(v) = \frac{1}{\sqrt{2\pi\ \sigma^2}} \int_{-\infty}^{\log(v)} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] \mathrm{d}\,x \tag{1}$$

In the equation, the variable x is the common logarithm of the value of velocity v. This equation is expressed by the normal distribution whose parameters of the mean μ and the standard deviation σ are summarized in Table 1.

Table 1 Parameters of the vulnerability function of wooden houses

Damege Level	Construction Age	μ	σ
Collapse, Severe	~ 1974	2.18	0.242
	1975 ~ 1984	2.30	0.256
	1985 ~	2.55	0.283
Moderate	~ 1974	2.05	0.293
	1975 ~ 1984	2.16	0.309
	1985 ~	2.48	0.355
Light	~ 1974	1.84	0.368
	1975 ~ 1984	1.95	0.391
	1985 ~	2.34	0.468

The two parameters of the normal distribution are shown in the table corresponding to the three damage levels and to the three construction ages. Because of taking the ground motions of the relative long return period into consideration, the values of μ and σ for the moderate damage level are selected. From the view of the seismic performance objective, the earthquake performance level is moderate damage and the earthquake design level is 500-year return period in this study. The relationships between damage rate of wooden houses and the peak ground velocity are shown in Figure 3.

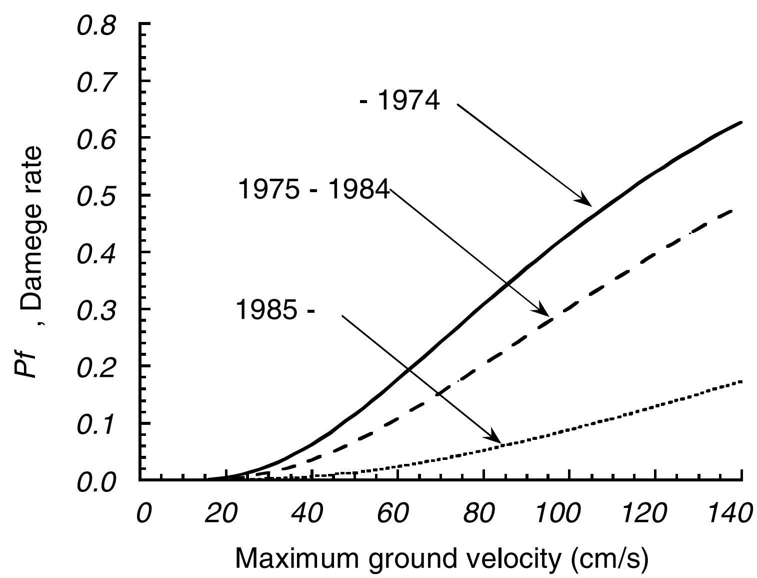


Figure 3 Relationship between damage rate of wooden houses and peak ground velocity

The solid line shows the vulnerability curve of buildings constructed before 1974, the break line and the dotted line show those of from 1975 to 1984 and after 1985, respectively. The damage rates are significantly affected by the construction ages. Therefore, the cities mainly consisted of the relatively weak buildings constructed before 1974 are very dangerous, but the seismic upgrading is rarely applied for the old wooden houses in Japan.

SEISMIC URBAN FACTOR

The new load factor which is available for constructing the new wooden houses in high densely inhabited area is developed as the seismic urban factor. The procedure of calculating this factor is explained by Figure 4 and equation (2). The value of seismic urban factor is defined as the enhancing rate of the distribution of the strength of buildings in one city. As shown in the figure, it is necessary to set the allowable disaster level to calculate the enhancing ratio. The allowable amounts of damaged buildings are assumed to 600 in this study based on the results of our previous study [4], where the relations between seismic disasters and the amounts of newspaper's reporting were investigated. It is considered that the seriousness of the social problems and disasters is appeared in the frequency of the daily news. The results of Ref.[4] showed that the excesses of 600 damaged buildings caused the serious social problems in Japan. The allowable disaster level is naturally variable according to the differences of countries and cultures and so on, then the value of 600 is only an assumption in this case. The main aim of this study is to convey the concept of this seismic urban factor which keeps same damage level of any cities with different populations and different seismic hazards.

The damage rate P_f is calculated by the equation bellow;

$$P_f = \mathrm{prob}\left[B < \frac{c}{g} LD \right] \tag{2}$$

where, the notations g and c show the gravitational acceleration and the transforming factor from velocity to acceleration, respectively. The value of c is assumed to 10.5 (1/s). The random variables B, L and D show the strength of buildings, the velocity and the amplification ratio, respectively. All of them are assumed to the log-normal distributions. The strength of buildings B is expressed as the base shear coefficient which is the ratio of the shearing capacity of first story divided by the weight of the building. These coefficients of variations of B and L are assumed to 0.50 and 0.36. For the random variable D, the mean value of 2.11 and the coefficient of variation of 0.27 are adopted up to the results of the study conducted by Newmark [5].

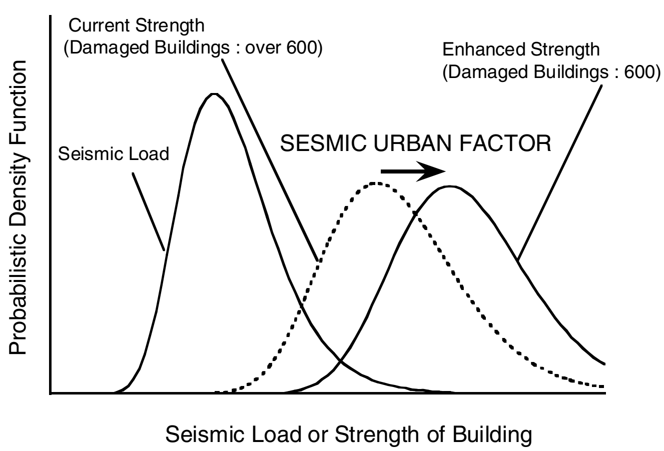


Figure 4 The concept of the seismic urban factor

The calculating procedure is shown as follows;

1) Input the velocity v and get the damage rate P_f using the equation (1).
2) Using the equation (2) and the damage rate P_f, calculate m_1 which shows the mean value of B before enhancing the strength.
3) Calculate m_2 which shows the mean value of B corresponding to the 600 damaged buildings.
4) Divide m_2 by m_1 to get k which shows seismic urban factor.

The seismic hazard level of one city is considered in the procedure 1) and the density of building is considered in the procedure 3). If the velocity v and the number of existing buildings in the target city are informed, the seismic urban factor can be calculated. However, it is not simple to solve the equation (2). The convergent answers are obtained numerically by the second-moment approach [6].

The samples of the calculated results are shown in Table 2.

Table 2 Seismic urban factors for model cities

Area	Velocity (cm/s)	Number of Housing	Rate of Number of Housing	Seismic Urban Factor	
				k_1	k_2
A	52.7	720000	16	**3.00**	**1.91**
		360000	8	**2.62**	**1.67**
		180000	4	**2.27**	**1.45**
		90000	2	**1.95**	**1.24**
		45000	1	**1.65**	**1.05**
		22500	1/2	**1.37**	0.88
		11250	1/4	**1.12**	0.71
B	40.6	720000	16	**2.39**	**1.56**
		360000	8	**2.09**	**1.36**
		180000	4	**1.81**	**1.18**
		90000	2	**1.55**	**1.01**
		45000	1	**1.31**	0.86
		22500	1/2	**1.09**	0.71
		11250	1/4	0.89	0.58
C	31.2	720000	16	**1.90**	**1.27**
		360000	8	**1.66**	**1.11**
		180000	4	**1.44**	0.96
		90000	2	**1.23**	0.82
		45000	1	**1.04**	0.70
		22500	1/2	0.87	0.58
		11250	1/4	0.71	0.47
D	24.0	720000	16	**1.50**	**1.03**
		360000	8	**1.31**	0.90
		180000	4	**1.14**	0.78
		90000	2	0.97	0.67
		45000	1	0.83	0.57
		22500	1/2	0.69	0.47
		11250	1/4	0.56	0.38
E	18.5	720000	16	**1.19**	0.84
		360000	8	**1.04**	0.73
		180000	4	0.90	0.64
		90000	2	0.77	0.54
		45000	1	0.65	0.46
		22500	1/2	0.54	0.38
		11250	1/4	0.44	0.31

In the table, the seven model cities are classified by the number of housing. From the statistical data obtained by Ref.[1], the city with 45,000 housings is set as the standard city. The number of 45,000 is the mean value of housings in total of 694 cities in Japan. The differences of five seismic hazard areas are informed in the table. The velocities v of each area are obtained by the seismic hazard of ground motion shown in the hazard map of Figure 2.

All components of the model cities are assumed to the detached wooden houses in order to apply the function proposed in Ref.[3]. The calculated values of the seismic urban factor k are shown in right side columns of the table. The difference of the value of k_1 and k_2 depends on the construction ages. The aging distribution of components of one city is modeled realistically based on the statistical data of Ref.[1]. And the aging distribution is adopted for calculating the values of k_1. On the other hand, the values of k_2 show the results on the assumption which all houses were built after 1985. The reason for assuming the two types of the cities is to observe the difference between current situation mixed with varieties of seismic performance levels and idealized situation consisted of only houses with higher seismic performance.

In the table, the colored cells show the larger value than 1.0 to identify the risky situations due to the occurrence of the severe disaster with excess of 600 damaged buildings. From the comparisons between k_1 and k_2, the value of k_2 is 0.64 times of the value of k_1 and colored cells of k_2 decrease significantly. The values of k_1 in the area 'C' are the almost same values of k_2 in the area 'A'. If the cities consisted of houses built after 1985 are constructed by a kind of new housing town project, the seismic urban factors are obtained as the values of k_2.

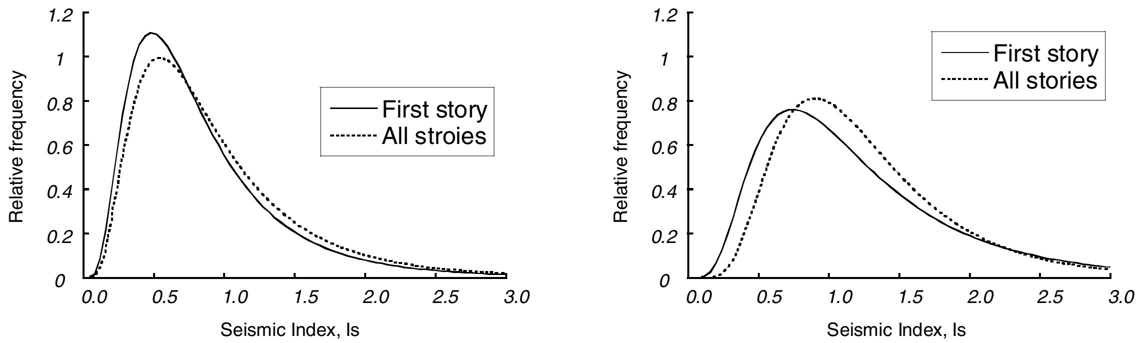
For the standard model city with 45,000 houses, the value of k_1 of the city in the area 'A' is 1.6 times greater than that in the area 'C'. This magnification is almost the same value of the ratio of the velocity in the area 'A' (52.7 cm/s) to that in the area 'C' (31.2 cm/s). In the same seismic hazard areas, the values of k_1 become 1.8 times when the numbers of housings become 16 times. This means that the 16 times crowded cities are necessary to enhance 1.8 times of the resistant capacity against the lateral force or to ensure the ductile capacity corresponding to the improved strength. The recommendations like 1.8 times enhancing the seismic performance are not so unrealistic to design and construct the building in urban area. If the required enhancement of the capacity is over 10 times, the factor will be meaningless for constructing the economical houses. On the established cases in this study, the proposed seismic urban factor is considered to be an useful index to avoid the serious problem caused by the excessively crowded inhabitants.

SEISMIC IMPROVEMENTS OF EXISTING RC BUILDINGS

In the previous section, the new factor which reduces the amounts of damaged buildings is proposed. The factor is developed to construct the new wooden houses in urban area by using the vulnerability function of equation (1). Therefore, there are few mentions about the existing buildings which are necessary to retrofit due to the lack of load carrying capacity and/or ductility. And there is also no mention about the other structural systems except for wooden one.

In this section, the effect of seismic upgrading on the reduction of amounts of damaged Reinforced Concrete (RC) buildings is discussed. The reasons for selecting the RC buildings are shown hereafter. The building code of Japan was revised in 1981 through the experiences of the 1968 Tokachi-oki Earthquake and the 1978 Miyagi-ken-oki Earthquake. As expected, most of the collapsed RC buildings by the 1995 Hyogo-ken Nanbu Earthquake were constructed before 1981, then the results showed the improvement of revised seismic design code of 1981. However, the earthquake revealed that a lot of the RC buildings with poor seismic resistant performance still remained. Because Japanese Government has been promoted seismic upgrading from the point of view of preventing the serious social problems after 1995, the seismic evaluations have been conducted widely especially for the public buildings. They are government offices, hospitals, schools and so on. In Japan, most of them are not wooden buildings but RC buildings because of the strict fire code. Hereafter, based on the distributions of seismic performance obtained by the 205 seismic evaluations of RC buildings in Kagoshima Prefecture in Japan, the rational target of upgrading is discussed. After the occurrence of the M6.2 Kagoshima-ken Hokuseibu Earthquake in 1997, the speedy seismic evaluations are carried out and over 450 results are obtained till 2003. The staffs of Kagoshima University have been cooperated with the structural engineers in conducting the seismic evaluations and upgrading. The current situations of seismic performance of RC buildings in each city are gradually obvious by the accumulated the data of seismic evaluations in all prefectures in Japan.

The distributions of the seismic index *Is* are shown in Figure 5.



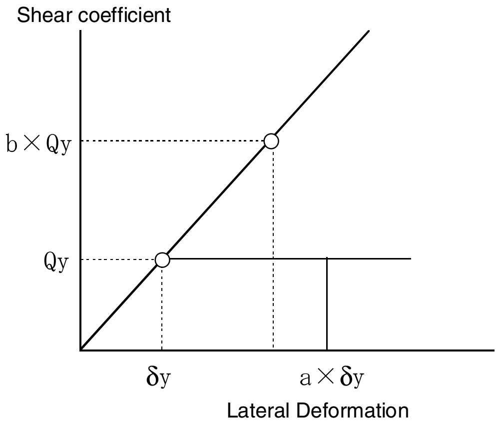
(a) Long-span direction **(b)Short-span direction**

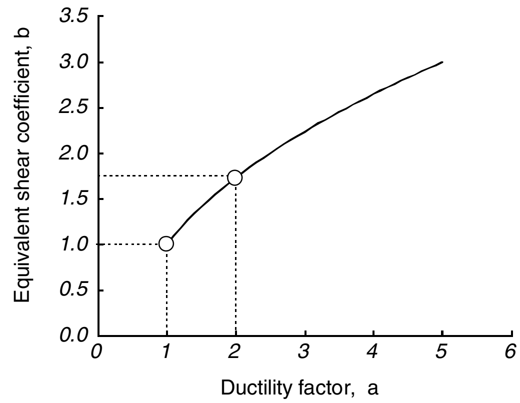
Figure 5 The distributions of seismic index, Is

The distributions of *Is* of long-span direction are shown in figure (a) and those of short-span direction are shown in figure (b). In this study, the seismic index *Is* is assumed the same value of the coefficient of shear capacity for each story and each one of two directions of building. The value of *Is* is essentially including the effect of deformation capacity, configuration and aging of the building. But these effects are neglected to simplify the discussion. The distributions are presumed the assembles of the shearing capacities of the buildings with the same deformation capacity. The solid line shows the distribution of 205 data which is assemble of only first stories of all buildings. The doted line shows the results of 500 data of all stories of the buildings. From the results of goodness of fit test, all curves are shown as the log-normal distributions.

It is observed from the figure that the long-span direction is significantly weaker than the short-span direction and the capacity of first story is slightly smaller than the other. The reasons are attributed to the feature of the buildings under the seismic evaluations in Japan. The school buildings make up 66 % of the samples, and they have low shearing capacity of long-span direction typically due to the large opening along the direction. The law of natural lighting and social convention compel that the all classrooms face south with large opening in normal Japanese schools. The East-West direction of school becomes long and weak consequently. The reason for high strength of short-span direction is the large load carrying capacities of shear walls located between the classrooms.

The distribution of *Is* of first story and long-span direction which is recommended to retrofit urgently is selected to discuss about the effect of seismic upgrading. The distribution is assumed to the log-normal distribution whose the mean value is 0.86 and the coefficient of variation is 0.68. Before the calculation is conducted concretely, the mean value of the distribution is increased by taking into account of plastic energy as shown in Figure 6.





(a) Responses of elastic and plastic system **(b)Equivalent shear coefficient**

Figure 6 Modifying the *Is* values for moderate damaged RC buildings

On the assumption that the ductility factor is 2 corresponding to the moderate damage level of RC buildings, the equivalent shear capacity becomes 1.7 times as shown in Figure 6 (b). The calculating procedure for the damaged rate P_f is also based on the equation (2). The mean value of the distribution of the strength of buildings *B* is expressed as the product of 1.7 and *Is*. The coefficient of variation of *B* is 0.68, it is the same as that of *Is*. The other parameters of *L* and *D* are the same as the values shown before.

For the model city consisted of 10,000 RC buildings, the relationships between *Is* and the amounts of the damaged buildings are calculated and shown in Table 3. The distribution of strength of the 10,000 RC buildings is equal to *B* assumed in the previous sentences. In the cases of eight levels of seismic hazard from 20 to 55 cm/s, the numbers of damaged buildings *Nd* are calculated according to increasing by 0.05 of *Is* from the non-upgrading value of 0.86.

Table 3 Results of seismic improvement

Velocity (cm/s)		Seismic Index, Is								
		0.86	0.91	0.96	1.01	1.06	1.11	1.16	1.21	1.26
20	Nd	174	116	78	51	34	23	15	10	7
	Rd	1.00	**0.67**	**0.45**	0.29	0.20	0.13	0.09	0.06	0.04
25	Nd	424	305	219	155	110	78	55	39	28
	Rd	1.00	0.72	**0.52**	**0.37**	0.26	0.18	0.13	0.09	0.07
30	Nd	796	607	456	342	257	192	142	106	79
	Rd	1.00	0.76	**0.57**	**0.43**	0.32	0.24	0.18	0.13	0.10
35	Nd	1273	1008	792	620	483	376	291	225	174
	Rd	1.00	0.79	**0.62**	**0.49**	0.38	0.29	0.23	0.18	0.14
40	Nd	1817	1491	1213	979	789	635	507	406	324
	Rd	1.00	0.82	0.67	**0.54**	**0.43**	0.35	0.28	0.22	0.18
45	Nd	2406	2026	1693	1410	1165	962	789	649	529
	Rd	1.00	0.84	0.70	**0.59**	**0.48**	0.40	0.33	0.27	0.22
50	Nd	3006	2592	2216	1886	1599	1346	1131	949	793
	Rd	1.00	0.86	0.74	0.63	**0.53**	**0.45**	0.38	0.32	0.26
55	Nd	3604	3164	2763	2397	2069	1779	1520	1300	1106
	Rd	1.00	0.88	0.77	0.67	**0.57**	**0.49**	0.42	0.36	0.31

In the area of 30 cm/s seismic hazard level, the amounts of damaged buildings decrease from 796 to 456 by upgrading *Is* from 0.86 to 0.96. The decreasing rate is 57%, and they are shown as the values of *Rd* in the table. The value in bold face in colored cell shows the around 0.5 of *Rd*. If *Is* is increased by 0.25 in the area with highest seismic hazard level of 55 cm/s, the amounts of damaged buildings will be half.

However, it needs heavy effort to make the total number of the damaged buildings equal in each area. For example, the value of *Is* of 1.26 is required in the seismic hazard level of 45 cm/s to decrease the damaged buildings within 600. The current situations of the cities in the high seismic hazard area are very dangerous. It is necessary to conduct the seismic upgrading urgently in such a place and this table is available for planning the seismic improvement. Because *Is* is technical index, the table is useful for explaining the effect of upgrading for public agency or community.

The results shown in Table 4 are obtained by almost the same manner except for the varying the coefficient of variation. If the seismic improvements are conducted in one city for some buildings, the distribution of the strength of buildings will vary narrowly. The standard deviations are decreased by 0.02 stepwise at every increasing by 0.05 of the value of *Is*. For example, the standard deviation is changed to 0.66 when the value of *Is* becomes 0.91. In the table, the colored cells which show around 0.5 of *Rd* shift to left side comparing to those in Table 3. The seismic upgrading with decreasing the variation of the distribution is very effective to reduce the amounts of damaged buildings as shown in Table 4. In order to obtain the distribution of the strength with small standard deviation easily, it is better to upgrade the extremely weak buildings primary.

Table 4 Results of seismic improvement considering the reduction of variation

Velocity (cm/s)		Seismic Index, Is								
		0.86	0.91	0.96	1.01	1.06	1.11	1.16	1.21	1.26
20	Nd	174	106	64	37	22	13	8	5	3
	Rd	1.00	**0.61**	**0.37**	0.21	0.13	0.08	0.04	0.03	0.02
25	Nd	424	285	187	122	79	52	33	21	14
	Rd	1.00	**0.67**	**0.44**	0.29	0.19	0.12	0.08	0.05	0.03
30	Nd	796	572	406	285	198	138	96	66	45
	Rd	1.00	0.72	**0.51**	**0.36**	0.25	0.17	0.12	0.08	0.06
35	Nd	1273	964	725	536	394	289	212	153	111
	Rd	1.00	0.76	**0.57**	**0.42**	0.31	0.23	0.17	0.12	0.09
40	Nd	1817	1443	1131	874	674	513	390	296	224
	Rd	1.00	0.79	**0.62**	**0.48**	0.37	0.28	0.21	0.16	0.12
45	Nd	2406	1976	1600	1285	1027	811	640	501	392
	Rd	1.00	0.82	0.67	**0.53**	**0.43**	0.34	0.27	0.21	0.16
50	Nd	3006	2542	2121	1757	1443	1176	951	770	618
	Rd	1.00	0.85	0.71	**0.58**	**0.48**	0.39	0.32	0.26	0.21
55	Nd	3604	3116	2667	2264	1903	1590	1321	1095	901
	Rd	1.00	0.86	0.74	0.63	**0.53**	**0.44**	0.37	0.30	0.25

CONCLUSIONS

The two approaches which aim to reduce the earthquake risk were discussed. The first approach was to propose a new design factor, seismic urban factor, which was intended to control the amounts of damaged buildings within the allowable disaster level. The factors were calculated according to the differences of density of buildings and seismic hazard level. The sample calculations were conducted for the model cities with seven different number of buildings and with five different earthquake hazard levels. From the table assembled of the results, the general trend of relationships between the seismic urban factors and the densities of buildings was obtained. For example, the value of the seismic urban factor became 1.8 times when the number of housings becomes 16 times in the same seismic hazard area. These recommendations to avoid the serious problem caused by the excessively crowded inhabitants were obtained by this study.

The second approach was to investigate the effect of seismic improvement by using the statistical data of seismic evaluations of RC buildings conducted in the real prefecture in Japan. The model city consisted of 10,000 RC buildings was used to calculate the amounts of damaged buildings parametrically according to the upgrading levels. The distribution of the strength were referred to the results of the seismic evaluations conducted in the real prefecture in Japan. The targets of seismic improvements for the model city were concretely calculated to make the amounts of damaged RC buildings half in the eight different seismic hazard areas. In the area with seismic hazard level of 55 cm/s, it is necessary to increase the shearing capacity by 0.25 to make the amounts of damaged buildings half from the non-upgrading situation. It was shown clearly that the relationship between the enhanced strength and reduction of the number of damaged buildings. The results were available for the real seismic upgrading projects.

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