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EFFECT OF SEISMIC RETROFIT ON SEISMIC RISK MITIGATION FOR REINFORCED CONCRETE BUILDINGS

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SUMMARY

Seismic evaluation and retrofit of existing buildings locates in a high seismic region is important to avoid destructive damage due to severe earthquakes. It is of great importance to assess the seismic risk of buildings and to decide a demand criterion for screening vulnerable buildings.

In this paper, the effect of seismic retrofit on seismic risk mitigation is investigated. First, the relationship between seismic capacity *Is*-Index and damage of reinforced concrete buildings suffered 1995 Hyogoken-Nambu Earthquake is discussed. Secondly, seismic capacity of R/C school buildings in Sendai City is statistically examined and distribution of seismic capacity *Is*-Index of total R/C school buildings is estimated. Then, Damage ratio due to simulated earthquakes, which are expected to attack Sendai City in the near future, is predicted by probabilistic approach for both with and without seismic retrofit. The repair cost of damaged buildings and number of injured or killed people are also predicted based on the evaluated damage ratio. Finally, the effect of seismic retrofit on seismic risk mitigation is discussed from a cost-effectivenss and human damage point of view.

1. INTRUDUCTION

Seismic evaluation and/or retrofit of existing buildings locates in a high seismic region is important to avoid destructive damage due to severe earthquakes. It is of great importance to assess the seismic risk of buildings and to decide a demand criterion for screening vulnerable buildings. In Japan, seismic capacity evaluation and strengthening have been applied to existing buildings especially after the 1995 Hyogoken-Nambu Earthquake. Judging criteria for screening retrofit candidates and required capacity level is generally set to harmonize with the current seismic code. However, there has been few study that tried to prove the effect of seismic retrofit on mitigation of seismic risk such as damage ratio, repair cost, and number of injuries and death induced by severe earthquakes.

In this paper, therefore, the effect of seismic retrofit is investigated. First, the relationship between seismic capacity *Is*-Index and damage of reinforced concrete buildings suffered 1995 Hyogoken-Nambu Earthquake is discussed. Secondly, seismic capacity of R/C school buildings in Sendai City is statistically examined and distribution of seismic capacity *Is*-Index of total R/C school buildings is estimated. Then, Damage ratio due to simulated earthquakes, which are expected to attack Sendai City in the near future, is predicted by probabilistic approach for both with and without seismic retrofit. The repair cost of damaged buildings and number of injured or killed people are also predicted based on the evaluated damage ratio. Finally, the effect of seismic retrofit on seismic risk mitigation is discussed from a cost-effectivenss and human damage point of view.

2. DAMAGE TO REINFORCED CONCRETE BUILDINGS DUE TO THE 1995 HYOGOKEN-NAMBU EARTHQUAKE

2.1 Damage Statistics

Damage survey and seismic capacity evaluation of reinforced concrete school buildings were carried out after the 1995 Hyogoken-nambu Earthquake by the Committee for School Buildings in the Architectural Insitute of Japan (AIJ)[1,2]. The working group for R/C structures investigated structural damage to a total of 631 reinforced concrete school buildings in Kobe City, Nishinomiya City, Awaji Island, and other neighboring cities subjected to a strong ground shaking. Damage statistics was shown in **Table 1** and **Figure 1**. Note that the Japanese seismic design codes for buildings were revised in 1971 and 1981. Specifications such as maximum spacing of hoops of reinforced concrete columns were revised to increase structural ductility in 1971, whereas the verification on the ultimate lateral load carrying capacity of designed structure by limit analysis or pushover analysis considering deformation capacity of members was required in 1981. Most of the buildings, which suffered from serious damage, were designed and constructed before 1981, and especially those before 1971 had extensive damage. On the other hand, most new buildings designed according to the current seismic codes enforced in 1981 showed fairly good performance and prevented severe structural damage even under such strong ground motion, and the ratio of moderately or more damaged school buildings was only 8%. These results reveal that the seismic capacity of existing R/C buildings in Japan has been improved significantly due to revisions of the seismic design codes. However, it is necessary, as had been often pointed out before the earthquake, to identify seismically vulnerable buildings designed based on old seismic codes and to upgrade their seismic capacity.

Table 1 Damage statistics of R/C school buildings due to 1995 Hyogoken-nambu Earthquake[2]

	Pre-1971	1971-1981	Post-1981	Total
Collapse	18 (5%)	2 (1%)	0	20 (3%)
Severe Damage	24 (7%)	9 (5%)	0	33 (5%)
Moderate Damage	90 (27%)	39 (24%)	11 (8%)	140 (22%)
Minor Damage	41 (12%)	21 (13%)	7 (5%)	69 (11%)
Slight or no Damage	159 (48%)	95 (57%)	115 (87%)	369 (59%)
Total	332 (100%)	166 (100%)	133 (100%)	631 (100%)

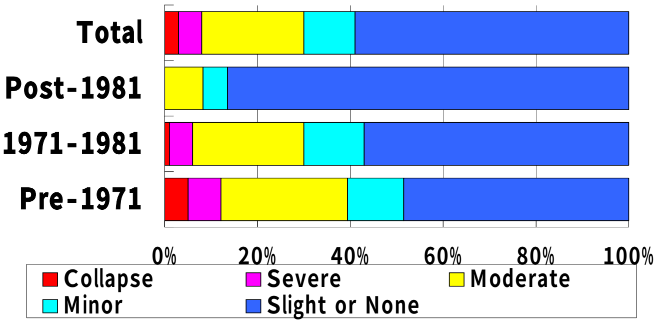


Figure 1 Damage ratio of R/C school buildings due to 1995 Hyogoken-nambu Earthquake [2]

2.2 Relationship between Seismic Capacity and Damage

Figure 2 shows the relationship between the seismic capacity index (*Is*-Index) and construction age of 82 R/C school buildings, where *Is*-Indices of each building are evaluated by the "Japanese Standard for Seismic Capacity Evaluation of Existing Reinforced Concrete Building"[3]. *Is*-Index can be calculated by Eq.(1) at each story and each direction.

$$Is = E_0 \times S_D \times T \qquad (1)$$

E_0 is a basic structural index calculated from the product of strength index (*C*), ductility index (*F*), and story index (ϕ), i.e., $E_0 = \phi \times C \times F$. *C*-Index denotes the lateral strength of the buildings in terms of shear force coefficient. *F*-Index denotes the ductility index of the building ranging from 0.8 (extremely brittle) to 3.2 (most ductile), depending on the sectional properties such as bar arrangement, member proportion, shear-to-flexural-strength ratio etc. ϕ is a modification factor to allow for the mode shape of the response along the building height. S_D and *T* are reduction factors to modify E_0 in consideration of structural irregularity and deterioration after construction, respectively.

The Seismic Evaluation Standard recommends as the demand criterion that *Is*-Index higher than 0.6 should be provided to prevent major structural damage or collapse. This criterion is based on the correlation study from the past earthquake damage and the calculated indices for the damaged buildings. Past experiences of the 1968 Tokachi-Oki, 1978 Miyagi-ken-Oki and other earthquakes reported that buildings with *Is*-Indices higher than 0.6 escaped severe damage or collapse. As can be found in **Figure 2**, *Is*-Indices for most of the buildings constructed before 1971 were less than 0.6, whereas they were more than 0.6 for those constructed after 1981. As mentioned earlier, the Japanese seismic design codes for buildings were revised in 1971 and 1981. The results shown in **Figure 2** indicated that seismic capacity of reinforced concrete school buildings in Japan were successfully improved due to the revisions of seismic design codes.

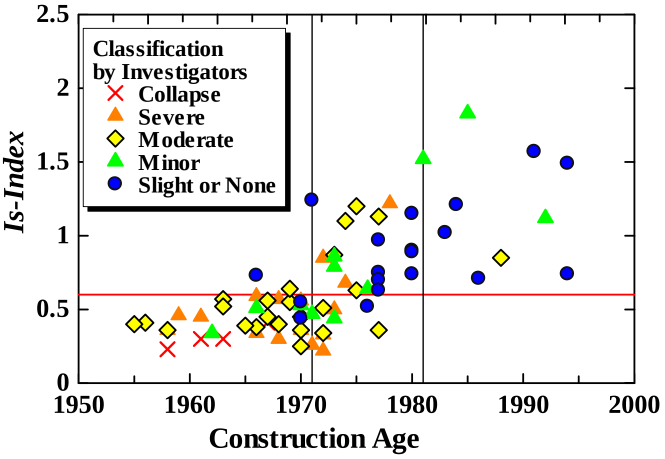


Figure 2 Construction age vs. seismic capacity *Is*-Indices of R/C school buildings

Figure 3 shows the relationship between *Is*-Index and damage level indices *R*-Index proposed in “Japanese Standard for Damage Level Classification of Reinforced Concrete Building”[4]. A fair correlation was observed between calculated *Is*-index and observed damage. Most of the buildings with *Is* values lower than 0.4 had major damage. Most buildings with *Is*-values lower than 0.3 were severely damaged or collapsed (R < 60). Those with *Is* values of 0.4 through 0.6 were moderately damaged or more. Many buildings with *Is* values higher than 0.6 avoided severe damage and had minor damage or less (R > 80). However, it should be noted that serious damage (R < 60) was observed in six buildings although their *Is* values were higher than 0.6, which was different from the past experiences. One of the possible reasons for such serious damage may be their failure modes different from other buildings with serious damage. These buildings were ductile frame structures with relatively lower lateral strength (*C*-Index) but large deformation capacity (*F*-Index). In these buildings, relatively ductile failure modes such as flexural failure, bond splitting failure etc., which might have more deformability than other buildings with brittle failure, were found. However, these 6 buildings were classified into *nearly collapsed* due to their relatively large residual displacements [2].

Is-Index of 0.6 is generally regarded as an effective demand criterion for screening seismically vulnerable buildings even though the exceptions mentioned above were found.

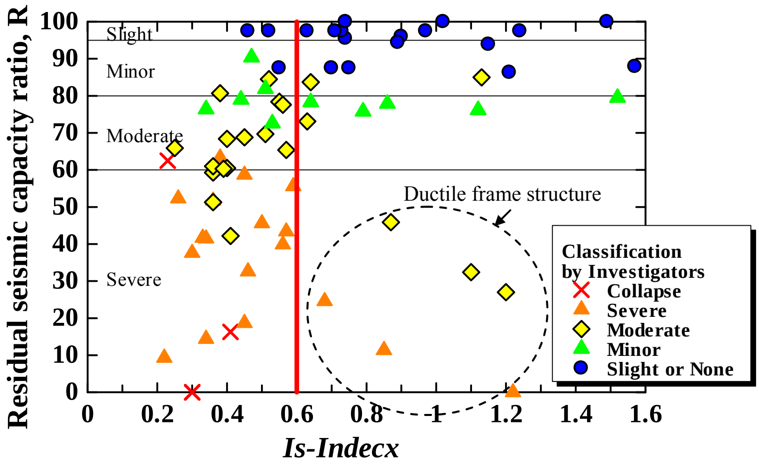
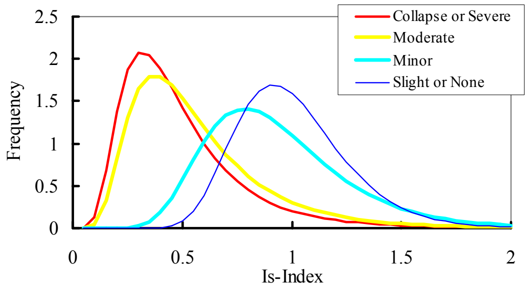


Figure 3 The second seismic performance indices and damage indices

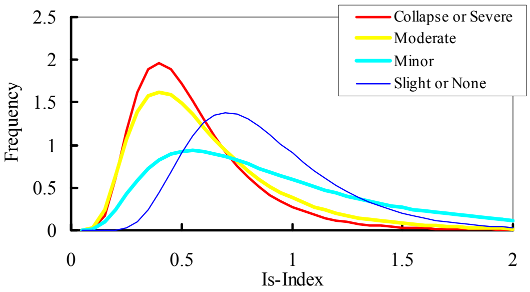
2.3 Evaluation of Relationship between Seismic Capacity *Is*-Index and Damage Provability

Figure 3 suggests damage to buildings is not deterministic but probabilistic, and uncertainty should be taken into account to assess seismic damage. Therefore, the relationship between *Is*-Index and damage probability was derived from the statistical data. **Figure 4** shows the distribution of *Is*-Indices of R/C school buildings with different damage levels, which was approximated by a log-normal probability density function. Seismic intensity VI and VII on JMA scale were observed in the affected area. The distributions of *Is*-Indices was estimated for each seismic intensity. **Table 2** shows damage ratio for seismic intensity VI and VII in Nishinomiya City and eastern part of Kobe City, where damage level of all the R/C school buildings was investigated by the AIJ's committee. The relationship between *Is*-Indices and damage probability can be obtained as shown in **Figure 5**, by summation of *Is*-Index distributions (**Figure 4**) for each damage level multiplied by the damage ratio (**Table 2**). The figure indicates reduction of damage probability with increase of Is-Indices. Estimated provability for moderate or more damage at Is=0.7 is 4% and 16% for seismic intensity of VI and VII, respectively.



average	Standard deviation
0.465	0.282
0.543	0.319
0.912	0.329
0.982	0.254

(a) **Seismic intensity VII**



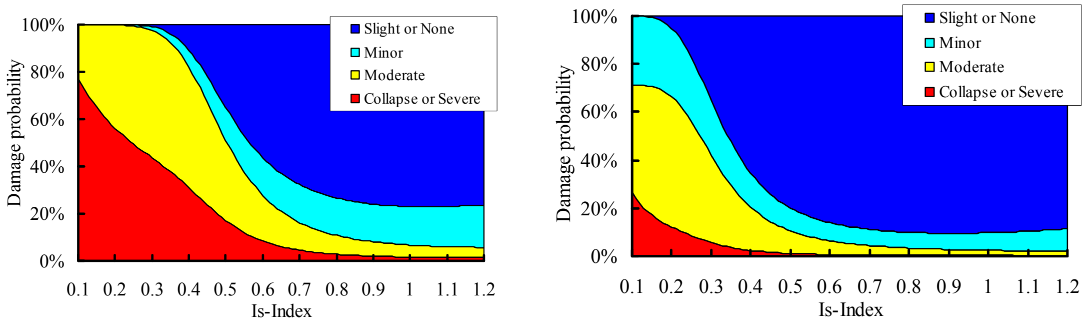
average	Standard deviation
0.528	0.273
0.599	0.364
0.998	0.738
0.857	0.351

(b) **Seismic intensity VI**

Figure 4 *Is*-Index distribution of buildings with different damage level

Table 2 Damage ratio in the area of seismic intensity of VI and VII

Seismic Intensity	Slight or None	Minor	Moderate	Severe or Collapse	Total
VII	99 60.0%	25 15.1%	26 15.8%	15 9.1%	165 100%
VI	202 83.5%	24 9.9%	14 5.8%	2 0.8%	242 100%



(a) Seismic intensity VII **(b) Seismic intensity VI**

Figure 5 Relationship between damage provability and *Is*-Indices

Japanese seismic intensity scale was revised in 1996 and Intensity V and VI were divided into "*upper*" and "*lower*". The revised seismic intensity is measured automatically with seismic intensity meters and announced rapidly to the public and officials[5]. JMA seismic intensity I is calculated by Eq.(2)

$$I = 2\log A + 0.94 \qquad (2)$$

Where, A: acceleration value, of which exceeding time is equal to 0.3 sec during an earthquake. Note that acceleration used for this calculation is a vector of 2 horizontal and vertical components of filtered observed ground acceleration, during the record.

Fragility curves for the new JMA seismic intensity were derived from the relationship between damage ratio and *Is*-Indices (**figure 5**). Damage provability for seismic intensity VI and VII were employed in the estimation and accumulated log-normal function was employed to approximate the fragility curve. Obtained fragility curves are shown in **Figure 6**.

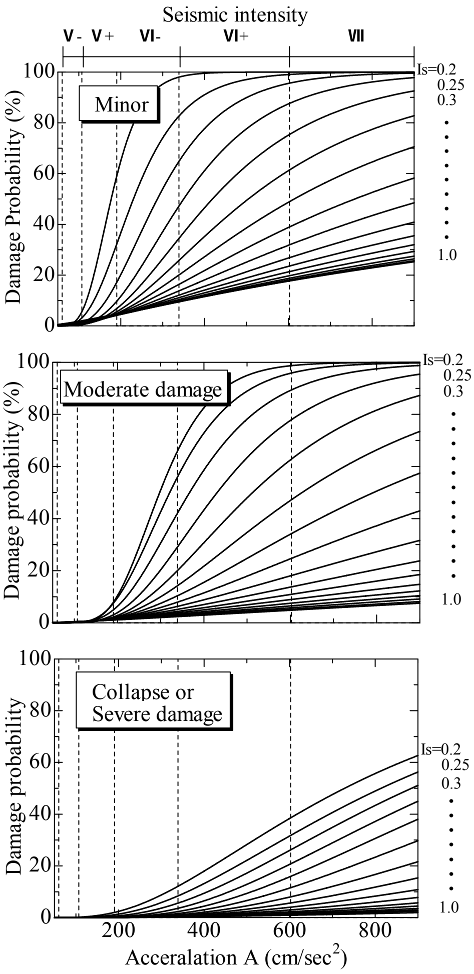


Figure 6 Fragility curve

3. SEISMIC CAPACITY OF R/C SCHOOL BUILDINGS IN SENDAI CITY

3.1 Progress of Seismic Evaluation and Retrofit of School Buildings in Sendai City

Seismic evaluation and retrofit has been applied widely to existing buildings in Japan after the “Law for promotion for seismic retrofit” was enforced in 1995. The Ministry of Education has been promoting seismic retrofit of school buildings throughout Japan. In the screening of retrofit candidates, Is = 0.7 is recommended as a demand criterion for school buildings, considering importance factor. The authors investigated the state of practice on seismic evaluation and retrofit of R/C school buildings in Sendai City. Result is shown in **Figure 7** and **Table 3**. In Sendai City, approximately 40% of 440 R/C school buildings, which are constructed after 1982 according to the current seismic codes, are considered to be provided with sufficient seismic capacity, whereas candidates for seismic evaluation and retrofit are as many as 60% (256 buildings). Sendai City began seismic evaluation and retrofit of the 256 buildings in 1996 and 234 have been already evaluated until 2003 as shown in **Figure 7**. As a result of the evaluation, a quarter of the evaluated buildings were provided with Is-Index of larger than required capacity of 0.7, whereas the rest (171 buildings) were judged as vulnerable and necessary to be retrofitted. Five buildings of the 171 candidates have been reconstructed and 97 buildings have been retrofitted until the end of last year. Assuming that the building constructed after 1982 and already retrofitted are provided with sufficient seismic capacity, approximately 80% of R/C school buildings in Sendai City are seismic resistant. This ratio indicates seismic retrofit in Sendai City is making rapid progress comparing with school buildings throughout Japan as shown in **Table 3**. Especially, 65% of existing buildings according to previous seismic codes have been retrofitted in Sendai City, on the other hand only 18% throughout Japan.

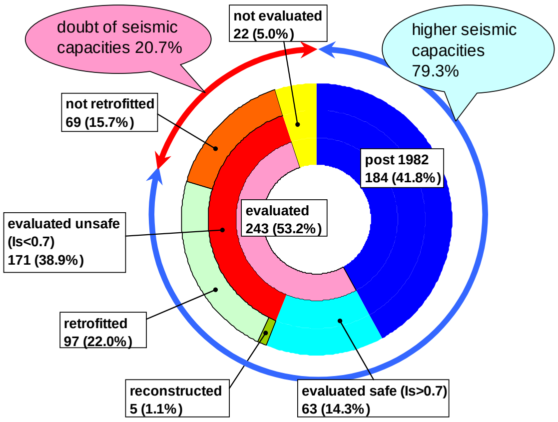


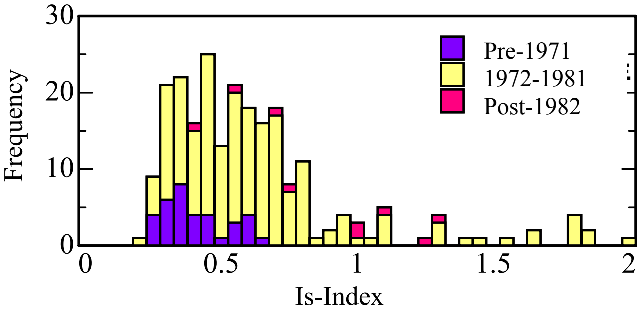
Figure 7 Ratio of seismic-evaluated and retrofitted R/C school buildings in Sendai City

Table 3 Comparison of progress on seismic retrofit between in Sendai City and Japan

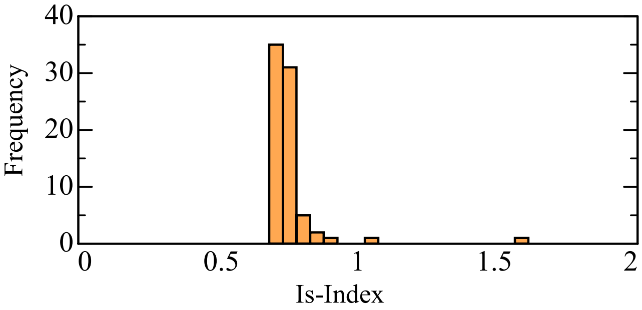
Number of Buildings	Sendai City	Japan
Total	440	151,624
Higher seismic capacity (retrofitted or post-1982)	349	69,588
Ratio	79.3%	45.9%
Constructed before 1981	256	100,243
Higher seismic capacity (retrofitted or post-1982)	165	18,207
Ratio	64.5%	18.2%

3.2 Estimation of *Is*-Index Distribution

Histogram of *Is*-Index of the 243 evaluated buildings is shown in **Figure 8**. Statistical data (average and standard deviation) of *Is*-Indices are shown in **Table 4**, classified by the construction year and need for retrofit. As can be seen from the figure, *Is*-Indices of most of “pre-1971” buildings are lower than 0.7, whereas the distribution of *Is*-Index shifts larger as the generation of the building becomes younger. This tendency is same as was observed in school buildings in Kobe area (Figure 2). Most of *Is*-Indices after retrofit of 97 buildings were concentrated around 0.75 (0.75 in an average with standard deviation of 0.11), because target capacity for retrofit *Iso*-Index of 0.7 is employed in Sendai City.



(a) Before retrofit



(b) After retrofit of retrofitted building

Figure 8 Histogram of *Is*-Index of evaluated school buildings in Sendai City

Table 4 Statistical data of *Is*-Index of evaluated school buildings In Sendai City

Construction year			Number of buildings	Average of Is	Standard Deviation
Pre-1981			234	0.60	0.33
	Is <0.7	Before retrofit	171	0.47	0.17
		After retrofit	76	0.75	0.11
	Is >0.7		63	1.33	0.81
Post-1982			9	0.90	0.30

Distribution of *Is*-Index of total school buildings in Sendai City was estimated based on the distributions obtained above. In the estimation following states were considered:

(a) *Without retrofit*: seismic upgrade of vulnerable buildings is not carried out at all. This state corresponds to the situation before 1995.

(b) *Present state*: 97 buildings of the 171 vulnerable buildings have been upgraded and 5 buildings have been reconstructed (Figure 7). As a result, approximately 80% of total buildings are provided with 0.7 or larger *Is*-Index.

(c) *Retrofit completed*: all the existing vulnerable building have been retrofitted so that *Is*-Index exceeds required seismic capacity, *Iso*-Index.

First, the buildings are categorized into 4 groups;

(a) Vulnerable buildings not yet retrofitted

(b) Retrofitted buildings

(c) Buildings needless to be retrofitted (Is>Iso)

(d) Buildings constructed after 1982

Then, histograms of each category multiplied in accordance with the number of the buildings were added up, assuming that distribution shape of each category is maintained if the number of building increased or decreased. Obtained histograms are shown in **Figure 9** together with type II asymptonic extreme-value distribution function.

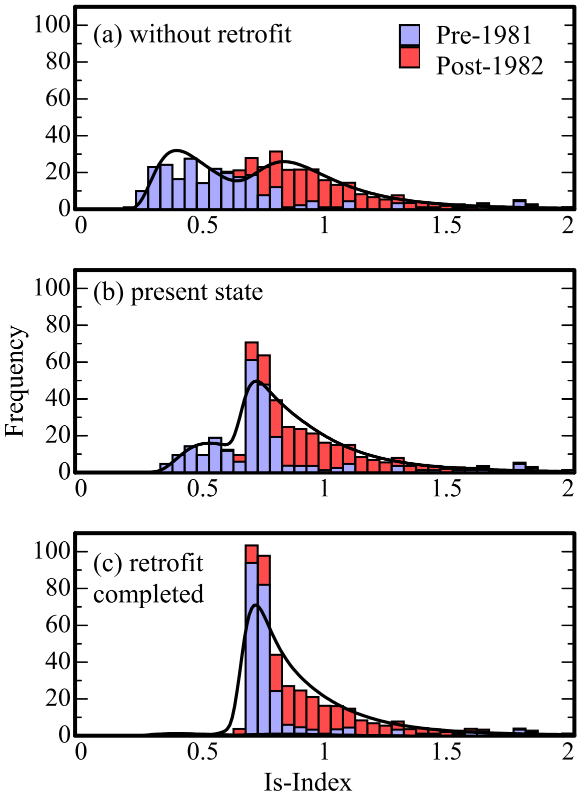


Figure 9 Estimated distribution of Is-Index for total school buildings in Sendai City

4. SEISMIC RISK ASSESSMENT FOR R/C SCHOOL BUILDINGS IN SENDAI CITY

4.1 Procedure of Seismic Risk Assessment

Seismic risk assessment of R/C school buildings in Sendai City was carried out using *Is*-Indices distribution and damage provability estimated above. Miyagiken-oki earthquake and Nagamachi-Rifu Fault earthquake were employed in the assessment considering past damaging earthquakes and affecting active fults. Miyagiken-oki earthquake, of which average return period is 37 years, is most hazardous earthquake in the region. The probability of occurrence in 20 years is approximately 90% according to the investigation by the Japanese Headquarters for Earthquake Research Promotions. The epicentre is located on off-coastal of Miyagi Prefecture. The 1978 Miyagiken-oki Earthquake induced severe damage in Miyagi Prefecture [6]. Nagamachi-Rifu Fault is an active fault located beneath Sendai City downtwon in the north-south direction. Return period of Nagamachi-Rifu Fault earthquake is considered longer than thousand years, therefore provability of occurrence is smaller than that of Miyagiken-oki earthquake. However, the damage may be expected larger if it occurred. Regional distribution of predicted seismic intensity in JAM scale due to the two earthquakes is shown in **Figure 10** [7]. Human activity is concentrated in the eastern part of the city, where larger intensity is predicted as shown in **Figure 10**. 88% of schools is located in the region of intensity “VI-“ for Miyagiken-oki earthquake, whereas 92% are in the region of intensity “VI+” for Nagamachi-Rifu earthquake.

Seismic risk assessment of R/C school buildings against the two hazardous earthquakes was carried out. *Is*-Index distributions in case of (a) “without retrofit”, (b) “present state” and (c) “retrofit completed” were employed in the damage assessment in order to discuss the effect of retrofit on mitigation of damage. In addition, *Is*-Index distributions in case that required seismic capacity *Iso*-Index was reduced from 0.7 to 0.4, 0.5 and 0.6 were considered. Procedure of assessment is as follows:

(1) Damage ratio of R/C school buildings was calculated based on the predicted seismic intensity at the site of each building and fragility-curve shown in Figure 6.

(2) Economical and human damage was estimated using calculated damage ratio. Repair costs for damaged buildings was evaluated and compared with the costs for strengthening of the vulnerable buildings before earthquake. The number of killed or injured was also estimated based the damage ratio.

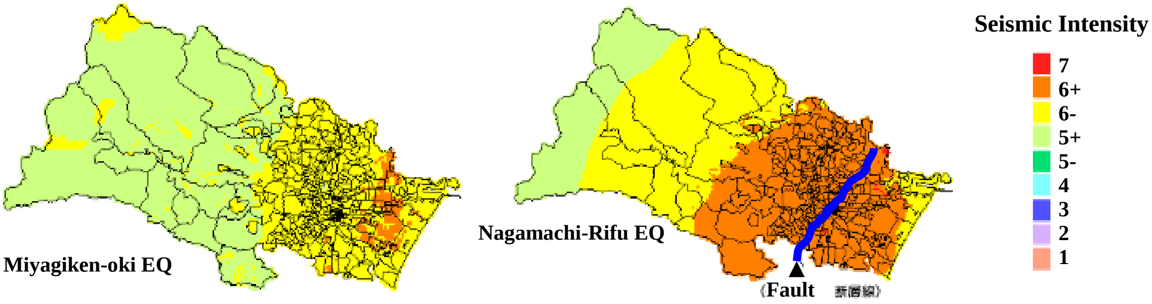
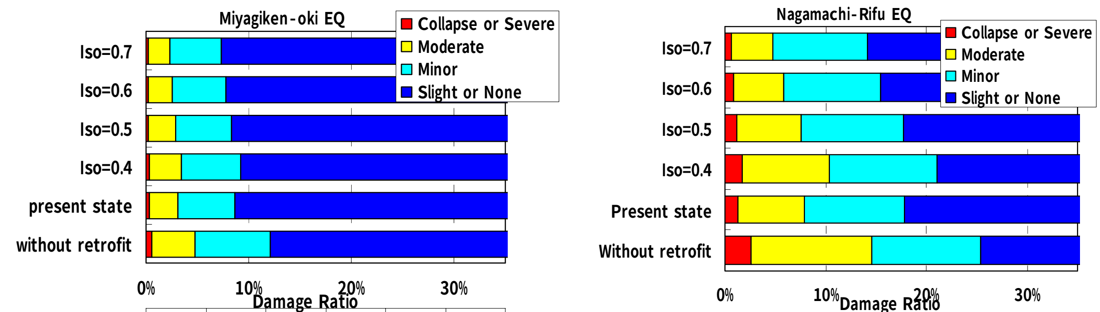


Figure 10 Distribution of predicted seismic intensity in Sendai City

4.2 Damage Ratio Estimation of R/C School Buildings

Figure 11 shows predicted damage ratio due to the two earthquakes. Damage ratio was calculated using the damage probability corresponding to the median of acceleration A in each seismic intensity range in Figure 6. In Figure 13, "*without retrofit*" and "*present state*" indicate damage ratio before seismic strengthening began and in the present state (102 buildings of 173 vulnerable ones have been retrofitted), respectively. *Iso*=0.4, 0.5, 0.6 and 0.7 indicate the results assuming seismic retrofit of all the buildings with *Is*-index of lower than *Iso*-Index have been completed. Note that *Iso* of 0.7 is, as mentioned earlier, recommended generally as required *Is*-Index for school buildings in Japan. Cases with *Iso* of 0.4, 0.5 and 0.6 were considered in order to discuss the effect of seismic retrofit.

The ratio of severe, moderate and minor damage to school buildings due to the 1978 Miyagiken-oki Earthquake is reported to be 1.2%, 3.7% and 7.3%, respectively, as shown in Table [6]. Predicted damage ratio without retrofit for Miyagiken-oki earthquake agrees well with these damage experiences. Damage ratio of heavy damage due to Nagamati-Rifu earthquake, which is an inland earthquake, is predicted much larger than that due to Miyagiken-oki earthquake. Comparing before and after retrofit, the effect on mitigation of potential risk can be found. Predicted ratio for moderate or more damage in present state was reduced to 50-60% of those before retrofit by the seismic strengthening of the 102 vulnerable buildings.



	without retrofit	present state	Iso=0.4	Iso=0.5	Iso=0.6	Iso=0.7
🟦 Slight or None	87.84	91.29	90.73	91.70	92.27	92.62
🟦 Minor	7.35	5.55	5.81	5.40	5.15	5.08
🟨 Moderate	4.28	2.84	3.13	2.64	2.34	2.09
🟥 Collapse or Severe	0.52	0.32	0.33	0.27	0.24	0.21

	Without retrofit	Present state	Iso=0.4	Iso=0.5	Iso=0.6	Iso=0.7
🟦 Slight or None	74.61	82.22	78.94	82.32	84.58	85.88
🟦 Minor	10.76	9.92	10.65	10.09	9.58	9.33
🟨 Moderate	12.05	6.60	8.74	6.42	4.95	4.08
🟥 Collapse or Severe	2.58	1.26	1.68	1.18	0.88	0.70

Figure 11 Predicted damage ratio

Table 5 Damage statistics of school buildings due to the 1978 Miyagiken-oki Earthquake

Damage level	Severe	Moderate	Minor	Slight or None	Total
Number of buildings (ratio)	1 (1.2%)	3 (3.7%)	6 (7.3%)	72 (87.8%)	82 (100%)

4.3 Assessment of Repair Cost and Casualty

The cost for retrofitting the vulnerable buildings before the earthquake and repair cost of the damaged buildings were evaluated using the predicted damage ratio. Evaluation procedure is as follows;

(1) Cost for retrofit, C_{Rt}, of each building can be calculated by Eq.(3)

$$C_{Rt} = U_{Rt} \times A_f \times 10\Delta Is \quad (3)$$

$$\Delta Is = {}_R Is - Is \quad (4)$$

Where, U_{Rt}: unit cost for retrofit per floor area required to increase 0.1 in Is-Index, A_f: total floor area of the building, ${}_R Is$: Is-Index after retrofit, ΔIs: increase in Is-Index

Table 6 shows costs for retrofit of the 97 school buildings in Sendai City. The average Is-Index after strengthening, ${}_R Is$, was 0.75 and total expense was 5,020 million yen. These gives a unit retrofit cost U_{Rt} 5,400(yen/ m^2 ΔIs0.1), which is retrofit cost per floor area required for increase 0.1 in Is-Index.

(2) Repair cost, C_{Rp}, can be be calculated by Eq.(5).

$$C_{Rp} = \sum A_f \times \left(U_1 \times D_1 + U_2 \times D_2 + U_3 \times D_3\right) \quad (5)$$

Where, ΣA_f: total floor area of all the school buildings in Sendai City (=1,019,827m^2),

U_1, U_2, U_3: unit repair costs for collapsed or severely damaged, moderately damaged, and minor damaged buildings, respectively,

D_1, D_2, D_3: damage ratio of collapsed or severely damaged, moderately damaged, and minor damaged buildings, respectively.

Table 6 shows statistical data of repair costs per floor area derived from investigation of school buildings damaged due to the 1995 Hyogoken-nambu Earthquake [8]. Note that costs for reconstruction is shown in collapsed or severely damaged buildings, because almost of severely damaged buildings were demolished and reconstructed after the earthquake.

Table 6 Cost for retrofit of R/C school buildings in Sendai City

	Total floor area ∑Af	Average ΔIs	Total retrofit cost	Unit retrofit cost
Retrofitted 97 buildings	265,472 (m^2)	0.35	5,020 (million yen)	5,400 (yen/m^2 ΔIs0.1)

Table 7 Repair cost of school buildings suffered the 1995 Hyogoken-nambu Earthquake (Yen/m^2)

Damage level	Collapse or Severe	Moderate	Minor	Slight or None
Unit repair cost	213,000 (reconstruction)	17,200	3,100	0

Evaluated costs for retrofit and repair are shown in **Figure 12**. In the figure, upper and lower limit of repair costs, corresponding to maximum and minimum damage provability in each range of seismic intensity in Figure 6, are also shown. The costs for retrofit spent until 2003 exceeds predicted repair costs without retrofit for Myagiken-oki earthquake, though the repair costs are reduced by strengthening of 97 buildings. The median of summation of retrofit and repair costs for every case is larger than predicted repair cost without retrofit. The upper limit of the summation is lowest for Iso=0.4, and the costs for Iso=0.5 is lower than the costs wituout retrofit. These results suggest Iso=0.4 or 0.5 may be enough for the required seismic capacity from cost effectiveness point of view, even if considering uncertainty of repair costs. On the other hand, the effect of seismic retrofit on mitigate of the repair costs can be found clearly for Nagamachi-Rifu earthquake. Predicted repair cost in the present state is reduced to approximately 50% and the summation of costs for retrofit and repair is smaller than repair cost without retrofit. The upper limit of the summation decreases as increase of *Iso*-Index, although apparent differences can not be found in the median of the summation. These results, suggest Iso=0.6 or 0.7 may be appropriate as a demand criterion against Nagamachi-Rifu earthquake.

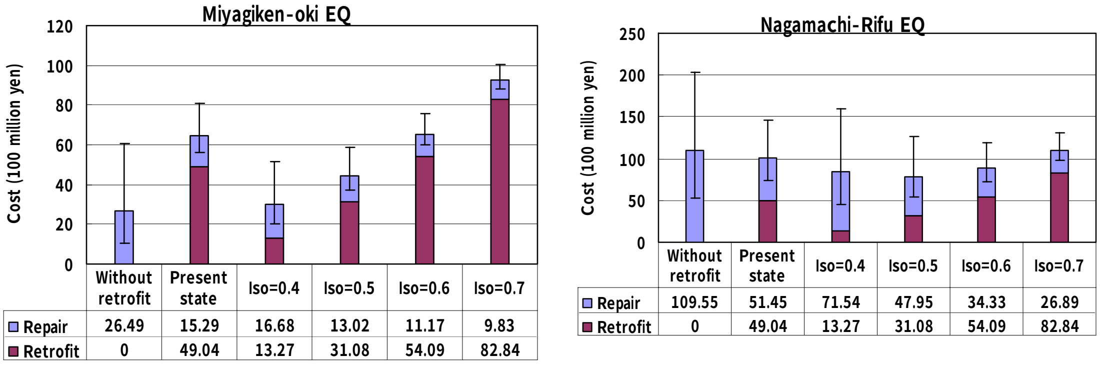


Figure 12 Predicted repair and retrofit costs

The number of casualties due to the two earthquakes is evaluated based on the predicted damage ratio. In the evaluation, equations in Ref [7], which are derived from damage experiences due to the 1995 Hyogoken-nambu earthquake, was employed.

The death toll, N_d, was evaluated by Eq.(6).

$$N_d = 0.078 \times D_1 \times N_t \tag{6}$$

Where, D_1: ratio of collapsed or severely damaged building, N_t: number of students and staffs in all the schools in Sendai City (=130,403).

The injured toll, N_i, was evaluated by Eq.(7).

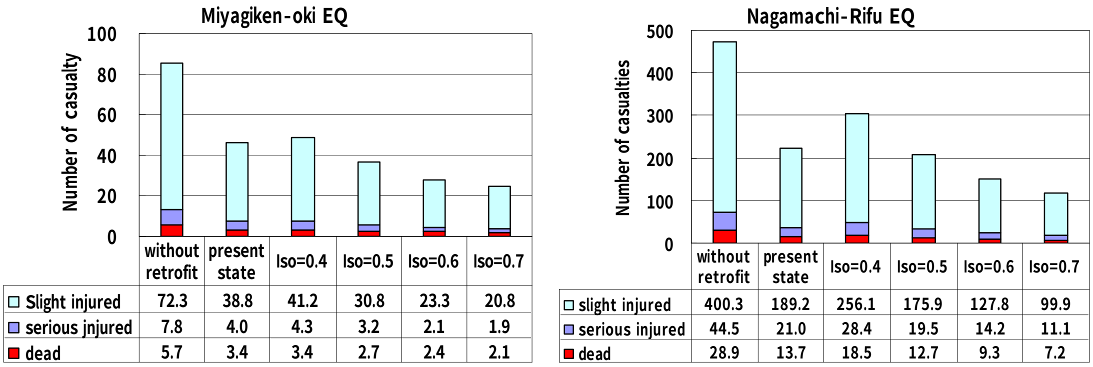
$$N_i = \begin{cases} 0.12 \times D_1 \times N_t & (0 < D_1 \le 0.25) \\ (0.07 - 0.16 \times D_1) \times N_t & (0.25 < D_1 \le 0.375) \\ 0.01 \times N_t & (0.375 < D_1) \end{cases} \tag{7}$$

Ratio of seriously injured to total injured, α_s, is calculated by Eq.(8).

$$\alpha_s = \begin{cases} 0.1 & (D_1 < 0.1) \\ 0.15 - 0.5 D_1 & (0.1 \le D_1 < 0.2) \\ 0.05 & (0.2 \le D_1) \end{cases} \tag{8}$$

Note that number of killed or injured predicted above corresponds to human damage assuming an earthquake occurs in daytime when students and staffs stay in school facilities.

Predicted casualty obtained from equations above is shown in **Figure 13**. Obvious mitigation of the number of casualties after seismic retrofit can be observed for both earthquakes in the figure. The predicted number of casualties in present state could be reduced to about half by the seismic retrofit performed until 2003. The number of casualties after retrofit completed with *Iso* of 0.4 is almost same or slightly more than those in present state. On the other hand, in case *Iso* of 0.7, the number is a quarter of those without retrofit. Killed or seriously injured persons due to Miyagiken-oki earthquake are relatively few (less than 10) even if without retrofit, whereas effect of seismic retrofit on mitigation of killed or seriously injured is observed for Nagamachi-Rifu earthquake. It may be important , as discussed herein, to take into account the effect of seismic retrofit such as mitigation of casualty as well as cost effectiveness in order to decide reasonable required seismic capacity level.



	without retrofit	present state	Iso=0.4	Iso=0.5	Iso=0.6	Iso=0.7
☐ Slight injured	72.3	38.8	41.2	30.8	23.3	20.8
▨ serious jnjured	7.8	4.0	4.3	3.2	2.1	1.9
■ dead	5.7	3.4	3.4	2.7	2.4	2.1

	without retrofit	present state	Iso=0.4	Iso=0.5	Iso=0.6	Iso=0.7
☐ slight injured	400.3	189.2	256.1	175.9	127.8	99.9
▨ serious injured	44.5	21.0	28.4	19.5	14.2	11.1
■ dead	28.9	13.7	18.5	12.7	9.3	7.2

Figure 13 Predicted casualty

5. CONCLUDING REMARKS

In this paper, a methodology to estimate potential seismic risk of R/C buildings was presented. The methodology was applied to school buildings in Sendai City, and the effect of seismic retrofit on the damage mitigation was discussed. Results can be summarized as follows.

(1) Relationship between seismic capacity *Is*-Index and damage probability was estimated from the statistical data of buildings damaged due to the 1995 Hyogoken-nambu Earthquake, and its applicability was examined. The damage ratio predicted agreed well with damage experience in the 1978 Miyagiken-oki Earthquake.

(2) Economical and human damage for R/C school buildings were evaluated for two hazardous simulated earthquakes in Sendai City, and the damage mitigation by seismic retrofit was found. Moreover, reasonable level of required seismic capacity was discussed from cost effectiveness point of view. Required seismic capacity *Iso* may be reduced to 0.4 or 0.5 against a predicted off-coastal earthquake, of which probability of occurrence is extremely high, whereas *Iso* of 0.6 or 0.7 is recommended considering an inland earthquake with lower probability of occurrence but severer shaking.

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