SEISMIC RISK ASSESSMENT OF BUILDINGS IN AN EARTHQUAKE-PRONE AREA IN JAPAN

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SUMMARY

For an effective earthquake preparedness against future earthquakes, it is essential to develop a rational methodology to predict earthquake damage in earthquake-prone countries. This paper describes a basic concept to estimate structural vulnerability of existing buildings based on the probabilistic studies on seismic capacities of existing reinforced concrete buildings and damage statistics due to past severe earthquakes in Japan. The application of the concept to the seismic risk assessment of existing buildings in an urban area in Japan, where a large scale earthquake is predicted to occur in the near future, is also described.

INTRODUCTION

It is of great importance to assess the seismic risk of existing buildings in an earthquake-prone area for mitigating destructive damage to buildings and for providing effective earthquake preparedness measures against future earthquakes. For this purpose, it is essential to develop a methodology to estimate the seismic capacity of buildings and their vulnerability, and to predict losses due to earthquakes.

It is also well recognized, however, that structural safety may be rarely evaluated with certainty due to uncertainties of ground motion, ultimate strength and ductility of structures, and earthquake response etc., and it should be regarded probabilistically rather than deterministically. From this point of view, the authors proposed a methodology to assess structural damage ratios due to earthquakes, in which the relationship of seismic capacity and damage ratio due to past severe earthquakes in Japan and the probabilistic approach to predict the damage to a future earthquake are considered.

Based on the statistical data and probabilistic studies on the seismic capacity of existing reinforced concrete buildings in Japan, this paper describes 1) the basic concept for the seismic risk assessment of existing buildings and 2) its application in an urban area in Japan where a large scale earthquake is predicted to occur in the near future.

SEISMIC CAPACITY OF EXISTING AND DAMAGED BUILDINGS

In the Shizuoka Prefecture located about 150 km south-west from Tokyo Metropolitan area (***Fig. 1***), a large scale earthquake of Richter magnitude 8.0 named the hypothetical "*Tokai Earthquake*" is predicted to occur in the near future from seismological point of view. The Shizuoka Prefectural Government, therefore, has carried out an enthusiastic earthquake preparedness program since 1977. One of the most essential issues in the program is seismic evaluation of existing buildings and seismic retrofitting of vulnerable buildings. From this

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point of view, more than 3,000 reinforced concrete public buildings including schools, hospitals and municipal offices were evaluated and some of them were retrofitted or demolished.

Fig. 1: Location of Shizuoka Prefecture

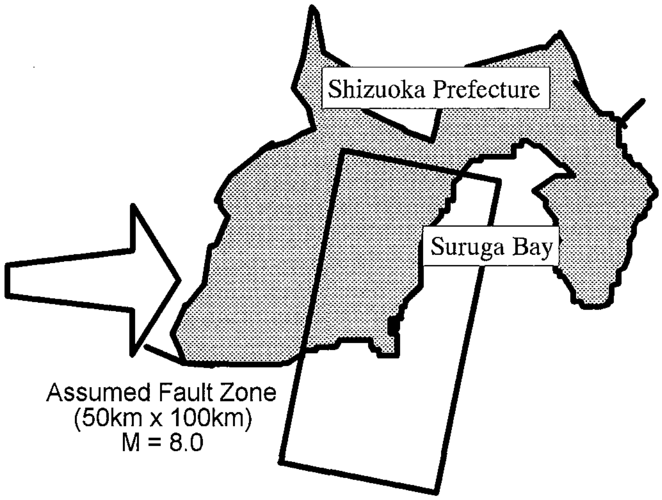

Fig. 2 shows a histogram of seismic capacity index (Is–index) of 1,615 existing reinforced concrete buildings in the Shizuoka Prefecture, where the index of each building in both principal directions are evaluated by the "Japanese Guideline for Evaluation of Seismic Capacity of Existing Reinforced Concrete Buildings[1]."

The *Guideline* evaluates the seismic capacity at each story and in each direction of a building by the following index:

$$I_S = E_O \cdot S_D \cdot T \qquad (1)$$

where,

E_O = basic structural index calculated by the ultimate horizontal strength, ductility, number of stories and the story level concerned,

S_D = structural design index to modify the Eo–index due to the irregularity of the building shape and distribution of stiffness along the height, and

T = time index to modify the Eo–index due to the deterioration of strength and ductility.

Most of the 1,615 buildings are three or four storied school buildings, designed and constructed before the revision of Japanese seismic code in 1970. As shown in the figure, the distribution of the Is–indices may be approximated by a log–normal probability density function (curve (1)). Since the Japanese seismic code may be considered uniform throughout the country, the distribution pattern of seismic capacities shown in ***Fig. 2*** can be considered a general tendency of existing reinforced concrete buildings in Japan.

PROBABILISTIC APPROACH FOR DAMAGE ASSESSMENT

The hatched area in ***Fig. 2*** shows a histogram of Is–indices for moderately or severely damaged buildings due to 1968 Tokachi–oki and 1978 Miyagiken–oki Earthquakes. In this figure, the frequency of damaged buildings was modified so that the number of damaged buildings should be 10 % of the total, because the damage ratios due to these two earthquakes were approximately 10%[2],[3].

Fig. 2 suggests that the earthquake damage is not deterministic but probabilistic, and the uncertainty of ground motion, ultimate strength, ductility, and earthquake response etc. should be taken into account to assess earthquake damage. ***Fig. 3*** shows a schematic expression of the Is–index of both existing and damaged buildings. The shape of ***Fig. 2*** is quite similar to ***Fig. 3(b)***. If the required seismic capacity to survive an earthquake shown by E_T–index in ***Fig. 3*** is deterministic and hence structures with seismic capacities less than a certain value are totally damaged, the damage ratios in the past two earthquakes would be greater than 10% (***Fig. 3(a)***). ***Fig. 2*** reflects a probabilistic feature of decision criteria for screening sound buildings.

Defining p_{Is} and p_{ET} which represent the probability density function of seismic capacity (Is–index) and required seismic capacity in terms of Is–index, respectively, the damage ratio V, i.e., the ratio of damaged buildings to total buildings, is expressed by the following general formula shown in ***Eq. (2)***.

$$V = \int_0^{\infty} p_{Is}(x) \cdot [1 - \int_0^{x} p_{ET}(r)\, dr]\, dx \qquad (2)$$

$$v(x) = p_{Is}(x) \cdot [1 - \int_0^{x} p_{ET}(r)\, dr] \qquad (3)$$

The function p_{ET} means the probability distribution of required seismic capacity, E_T–index, and therefore the term in the square bracket represents the probability of failure for structures with Is–index equal to x. Note that the uncertainty associated with ground motion is only taken into account and the seismic capacity for each building is assumed deterministic in ***Eq. (2)*** to simplify the subsequent discussions.

Setting $v(x)$ as shown in ***Eq. (3)***, the term of $v(x)$ may be considered to represent the distribution of Is–indices of damaged buildings shown in ***Fig. 2***. Substituting the function p_{Is} in ***Fig. 2*** approximated by a log–normal probability density function (curve (1)) and the relative frequency of Is–indices of damaged buildings shown as hatched part in ***Fig. 2*** into ***Eq. (3)***, the probabilistic distribution of E_T–indices (p_{ET}) can be calculated as shown in ***Fig. 4***.

Assuming the normal distribution for p_{ET}, the probability density function of E_T–indices is obtained as shown in ***Fig. 4*** (curve (2)). The curve (3) in ***Fig. 2*** is obtained from ***Eq. (3)***, where the functions p_{Is} in ***Fig. 2*** (curve (1)) and p_{ET} in ***Fig. 4*** (curve (2)) are used. The distribution of damaged buildings is successfully simulated by the proposed procedure.

It should be noted that the earthquake intensity during both Tokachi–oki and Miyagiken–oki Earthquakes is assumed about 0.23g. In ***Fig. 5***, the damage ratios to 0.36g and 0.45g earthquake calculated by ***Eqs. (2)*** and ***(3)***, where the mean value of p_{ET} is multiplied in proportion to the ground acceleration level, are also plotted. The damage ratio is three times for 0.36g earthquake and five times for 0.45g earthquake as much as that for 0.23g earthquake, respectively.

In analogous, the approach shown above can be applied to investigate the effects by retrofitting in terms of damage ratios if the statistical data on the seismic capacities of retrofitted buildings are available. Detail discussions on this study can be found in Ref. [4].

SEISMIC RISK ASSESSMENT AGAINST TOKAI EARTHQUAKE

As a part of the earthquake preparedness program for the future Tokai Earthquake, the Shizuoka Prefectural Government carried out a project on the seismic risk assessment covering the entire prefectural area. The assessment encompassed wide aspects such as human losses and structural damage due to ground shaking, landslides, tsunami, fire etc. [5]. In this paper, structural damage expected to existing reinforced concrete buildings due to ground shaking will be described in the subsequent sections.

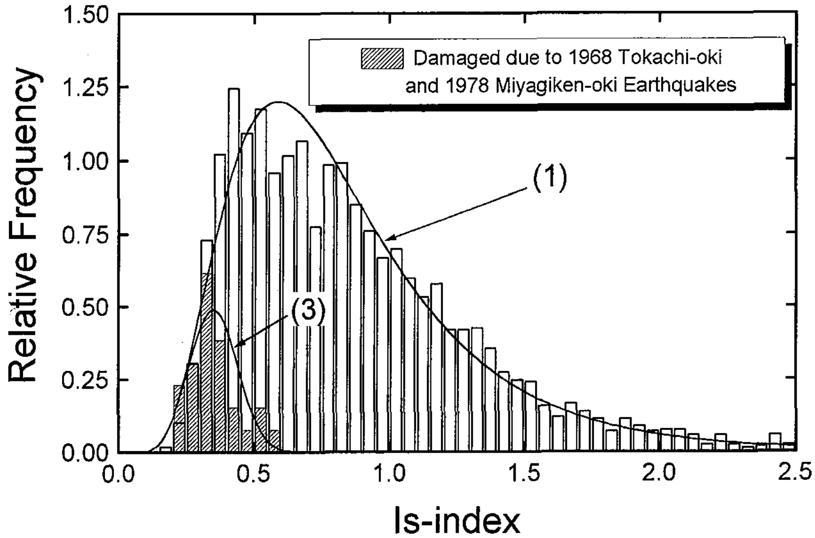

Fig. 2: Distribution of Is-index for existing and damaged buildings

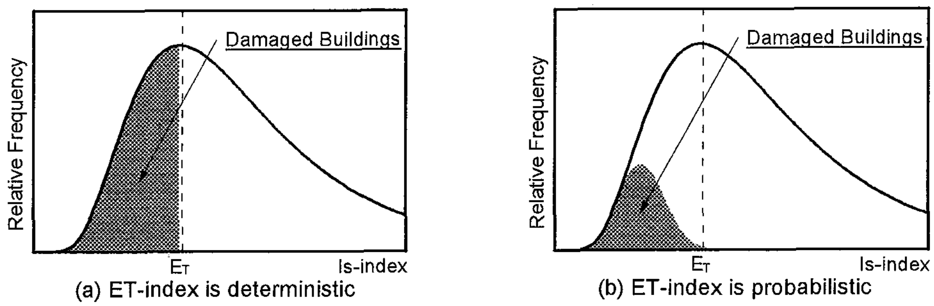

Fig. 3: Distribution of Is-index for damaged buildings

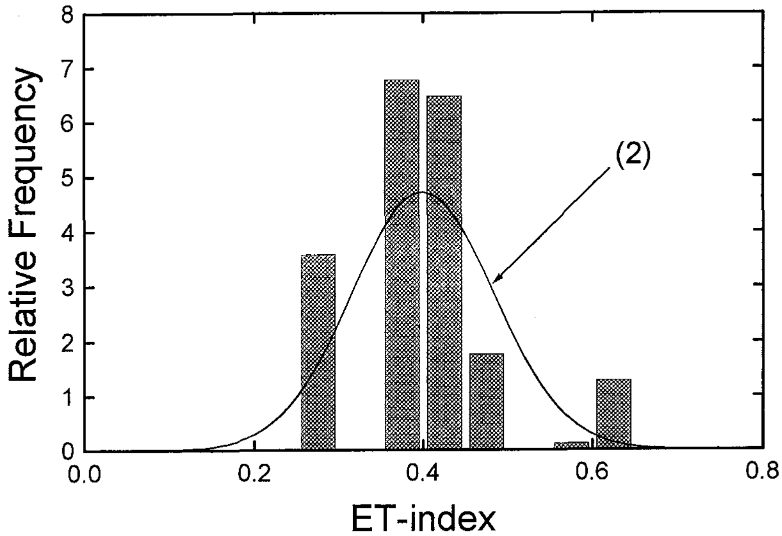

Fig. 4: Distribution of E_T–index

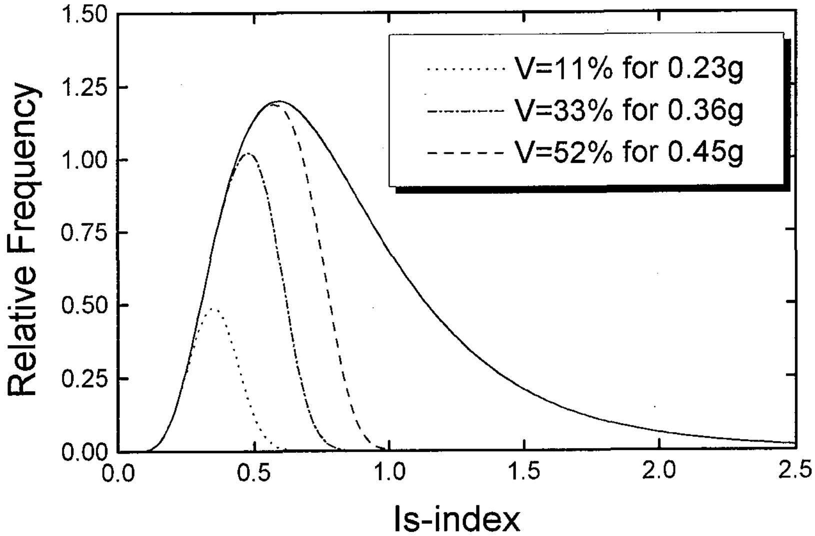

Fig. 5: Damage ratio, V, to different acceleration levels

General Concept

In the assessment, the expected peak ground acceleration due to the hypothetical Tokai Earthquake was first estimated and the number of structurally damaged buildings to the expected ground motion was then assessed. In estimating structural damage, two major factors, i.e., damage to 1) soil–structures due to liquefaction and to 2) superstructures due to earthquake response, were taken into account. It should be noted that buildings damaged due to ground failure are likely to reduce damage to superstructures by structural vibration. Therefore, the damage to soil–structures was first evaluated and the damage to superstructures was then evaluated excluding those damaged in soil–structures.

Microzonation and Expected Peak Ground Acceleration

The entire area involved in the Shizuoka Prefecture was divided into more than 30,000 unit areas with 500 m x 500 m square and each geological condition was surveyed. The expected peak acceleration on the base rock in each area was estimated by the empirical attenuation formula shown in ***Eq. (4)***, which was consistent with the damage level and estimated earthquake intensities due to Ansei–Era Tokai Earthquake in 1854. The peak ground acceleration (PGA) expected in each area was then calculated by multiplying the estimated acceleration on the base rock and the amplification factor considering the ground condition above the base rock.

$$A = 152.3 - 0.87\Delta \qquad (4)$$

A : peak acceleration on the base rock $(\mathrm{cm/sec^2})$

Δ : epicentral distance from the assumed fault (km)

Damage Estimation of Soil–structures due to Liquefaction

Each unit area was categorized in any one of zones I through III depending on the estimated possibility of liquefaction, in which the soil condition and the expected PGA were considered. In each categorized zone, the ratios of severe and moderate damage to soil–structure due to liquefaction were assumed, respectively, as shown in ***Table 1***.

Table 1: Assumed damage ratios of R/C buildings due to liquefaction

zone	possibility of liquefaction	pile	damage ratio	
			severe	moderate
I	high	provided	0 %	0 %
		not provided	20 %	30 %
II	medium	provided	0 %	0 %
		not provided	10 %	15 %
III	low or none	---	0 %	0 %

The damage ratios in zone I were derived from the evidence that approximately 20 % and 30 % of reinforced concrete buildings sustained severe and moderate damage to soil–structures, respectively, in an area where severe liquefaction was found during 1964 Niigata Earthquake[6]. In zone II, the damage ratios were tentatively assumed to be half of those in zone I. It should be noted that no damage was assumed in buildings with piles since the condition of foundation may significantly affect the damage level due to liquefaction.

The number of buildings that may be damaged due to liquefaction in a certain region can be then calculated from the number of buildings categorized in each zone within the region, the pile condition of buildings, and the ratios of severe and moderate damage as shown in ***Eq. (5)***.

$$N_{DL} = N_{DL(severe)} + N_{DL(moderate)} \qquad (5)$$
$$N_{DL(*)} = \sum_i (N_T \cdot A_i - N_{Pi}) \cdot V_{Li(*)}$$

N_{DL} : number of damaged buildings due to liquefaction in a certain region

$*$: damage level, i.e., severe or moderate

N_T : number of total buildings in a certain region

A_i : area ratio of zone i, i.e.,

= (area of zone i) / (area of a certain region)

N_{Pi} : number of buildings with piles in zone i

V_{Li} : damage ratio due to liquefaction (cf. *Table* 1)

i : zone category, i = I, II, or III (cf. *Table* 1)

Damage Estimation of Superstructures due to Ground Shaking

The probabilistic approach described earlier can be applied to estimate the number of damaged superstructures. It should be pointed out that the Japanese seismic code was revised in 1970 and in 1980 in the past three decades, and the seismic capacity of buildings highly depended on the year of their construction. Existing buildings were, therefore, classified into three groups according to the year of construction as shown in ***Table 2***.

The probability density function of seismic capacities, i.e., p_{Is} in ***Eq. (2)***, for each group was investigated based on the statistical data in the Shizuoka Prefecture and the ratio of moderately or severely damaged buildings to the acceleration level expected to building base was calculated from ***Eq. (2)***. The results are shown in ***Fig. 6***.

Table 2: Building groups and corresponding number of R/C structures in the Shizuoka Prefecture

group	year of construction	number of buildings
I	– 1970	20,117
II	1971 – 1979	19,459
III	1980 –	18,636

The number of damaged superstructures due to ground shaking in a certain region can be then calculated from the number of buildings categorized in each group within the region and the ratios of severe and moderate damage considering the expected acceleration level as shown in ***Eq. (6)***. As stated earlier, the buildings that are expected to have soil–structural damage are excluded in ***Eq. (6)*** so that the duplication may not cause overestimation of damage.

Note that V_{Sij} in ***Eq. (6)*** corresponds to the damage ratio V defined in ***Eq. (2)***, which includes both moderately and severely damaged buildings. In the assessment, each damage ratio is assumed equal reflecting the statistical evidence that both severe and moderate damage ratios to reinforced concrete buildings due to 1968 Tokachi-oki and 1978 Miyagiken-oki Earthquakes were about 5 %, respectively.

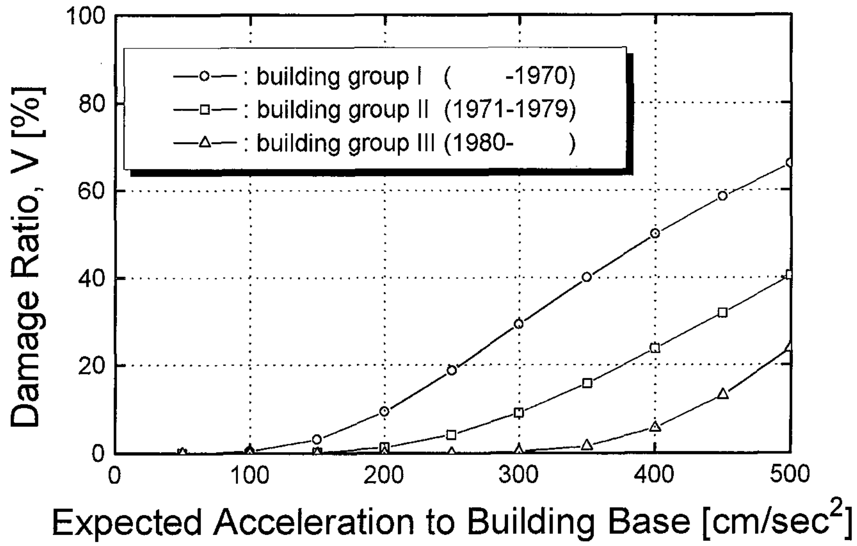

Fig. 6: Relationship between damage ratio V vs. expected acceleration

$$N_{DS} = N_{DS(severe)} + N_{DS(moderate)}$$

$$N_{DS(*)} = 0.5 \cdot \sum_j \sum_i (N_{ti} \cdot A_j) \cdot V_{Sij} \qquad (6)$$

N_{DS} : number of damaged superstructures in a certain region

* : damage level, i.e., severe or moderate

N_{ti} : number of total buildings categorized in group i in a certain region excluding N_{DL} in *Eq.* (5)

A_j : area ratio of zone j, i.e., = (area of zone j) / (area of a certain region)

V_{Sij} : damage ratio for group i in zone j (cf. *Fig.* 6)

i : building group, i = I, II, or III (cf. *Table* 2)

j : zone category with a certain expected acceleration level

Results of Seismic Risk Assessment of Structures

The number of buildings expected to be damaged in soil-structures and superstructures in each region was summed through the entire prefectural area and the final results were obtained.

Table 3 shows the final damage assessment of reinforced concrete buildings in the Shizuoka Prefecture due to ground shaking, together with those of other structural types. Note that the damage ratios to structures other than reinforced concrete building are estimated from tentative assumptions on their seismic capacities since enough statistical data are not available. The results shown herein are disclosed to the public to show the potential hazards in the Shizuoka Prefecture which will be significantly affected due to the future Tokai Earthquake and provide fundamental information for various pre– and post–earthquake operations.

Table 3: Estimated number of damaged buildings due to Tokai Earthquake

struc. type	total	damage to			
		soil–structures		superstructures	
		moderate	severe	moderate	severe
R/C	58,212	3,098 (5.3 %)	2,426 (4.2 %)	1,809 (3.1 %)	1,809 (3.1 %)
W	1,044,293	43,972 (4.2 %)	2,7258 (2.6 %)	171,527 (16.4 %)	19,809 (1.9 %)
S	148,621	7,606 (5.1 %)	4,056 (2.7 %)	18,045 (12.1 %)	10,483 (7.1 %)
others*	174,688	8,884 (5.1 %)	5,277 (3.0 %)	17,938 (10.3 %)	11,282 (6.5 %)

* : light–gage steel, stone masonry, concrete block masonry structures etc.

CONCLUDING REMARKS

The basic concept for seismic risk assessment based on the damage statistics due to past severe earthquakes and probabilistic studies were described. Development of seismic evaluation technique, acquisition of available data concerning seismic capacities of both existing and damage buildings, and acquisition of available damage statistics to calibrate the risk assessment model against historical evidence are most essential to develop a rational seismic risk assessment in an earthquake–prone area.

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