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Seismic Design Forces and Risks

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1. Introduction

In recent years, seismic damages caused by giant earthquakes have occurred in many countries. For example, over 250,000 people were killed by the Haiti Earthquake in January 2010. In addition, over 15,000 people were killed by the Tohoku Japan Earthquake and the coasts of Tohoku Japan were devastated by the massive tidal wave in March 2011.
Meanwhile, The Japanese seismic design criteria for road and railway bridges provide that two levels of earthquake motions – Level 1, which is small in scale but is generated frequently, and Level 2, which is intensive but is not generated frequently – must be used for the verification of seismic performance. For Level 1 earthquake motions, the elastic limit value of a structure is usually adopted as the seismic performance. For Level 2 earthquake motions, on the other hand, the limit value with which a structure does not collapse or is repairable is adopted as the seismic performance depending on the importance of the intended structure.
Level 2 earthquake motions used for verification are based on the records of strong motion seismograms obtained from the Hyogoken-Nanbu and other earthquakes, and seismic waveforms are assigned according to ground type. The earthquake motions are assigned according to classification of the land area of Japan categorized into three types by degree of seismic risk and adjusting the seismic motions using regional correction factors of 1.0, 0.85 and 0.7 depending on the regional classification.
Meanwhile, studies to calculate seismic waveforms unique to the target region of seismic design have been conducted in recent years. Seismic waveforms calculated in these studies were determined by carefully examining past seismic records, ground data, source models and other data of the target region from the viewpoint of earthquake and geotechnical engineering.
In reality, however, earthquakes that generate ground motions stronger than Level 1 but do not exceed Level 2 may occur during the service life of a structure. In current seismic design, direct consideration was not given to changes in performance and risk with seismic motions through time or the importance of applying effective repair and reinforcement methods. These factors cannot be taken fully into account by simply verifying the elastic limit or the limit of reparability or collapse of a structure subject to Level 1 or 2 earthquake motions based on the current seismic design force.
Many seismic risk management studies, which evaluated the loss (seismic risk) caused by the damage or collapse of a structure, have also been conducted in recent years. In these

papers, seismic risks were calculated using a hazard curve representing the probability of the generation of earthquake motions and a damage curve representing the probability of damage to the structure.
While this damage curve is calculated by statistical procedures using past damage records and analyses, it is necessary to define the damage to a structure with a single index, such as the top horizontal displacement or ductility factor. When damage is defined with an index, it is difficult to precisely associate the index with the repair for the damage. Therefore, these methods are considered difficult to apply them to the examination of seismic risks based on the definition of changes in the damage process and other details due to the difference in design.
To achieve these, it is first necessary to calculate design solutions reflecting the damage and collapse process of a structure under a uniform standard of value for various seismic forces. By calculating seismic risks for respective design solutions and comparing them for different seismic forces, it is possible to find the seismic force with which the total cost including the initial construction cost and seismic risk can be minimized. This is called the "target seismic design force" in this chapter. Although this method involves complex procedures, the necessity for target seismic design forces is expected to be higher for the design of long bridges and other structures that are highly important as lifelines from the viewpoint of the seismic risk management.
This chapter consists of the section presented below.
2. describes a design system with which design solutions are calculated using various seismic forces and the method for calculating the target seismic design forces. 3. explains the method for calculating seismic risks based on the definition of damage.
4. present the results of the analysis of an RC rigid-frame viaduct as Example of the calculation of the target seismic design forces.
While there is the possibility of loss caused by environmental and other effects besides those of earthquakes during the life cycle of a structure, such additional effects will be studied in the future and this paper limits its focus on the effects of earthquakes.

2. Target seismic design force

This section explains the method for calculating the target seismic design forces. In the case of design where the seismic risks of a variety of seismic forces are taken into account, it is assumed that the initial construction cost is low but the seismic risk is high for a structure designed for a low seismic force, while the seismic risk is low but the initial construction cost is high for a structure designed for a high seismic force. By quantifying this seismic risk based on the cost for the repair of damage and other factors to find the seismic risk cost, calculating the total cost by adding this to the initial construction cost and finding its relationship with the seismic force, the target seismic design force and the corresponding design solution can be obtained. Fig. 1 illustrates the flow of finding the target seismic design force and the corresponding design solution. Details of the flow are as described below.

2.1 Setting of the target structure and region

The type of the structure to be designed and the region where the structure will be constructed are set.

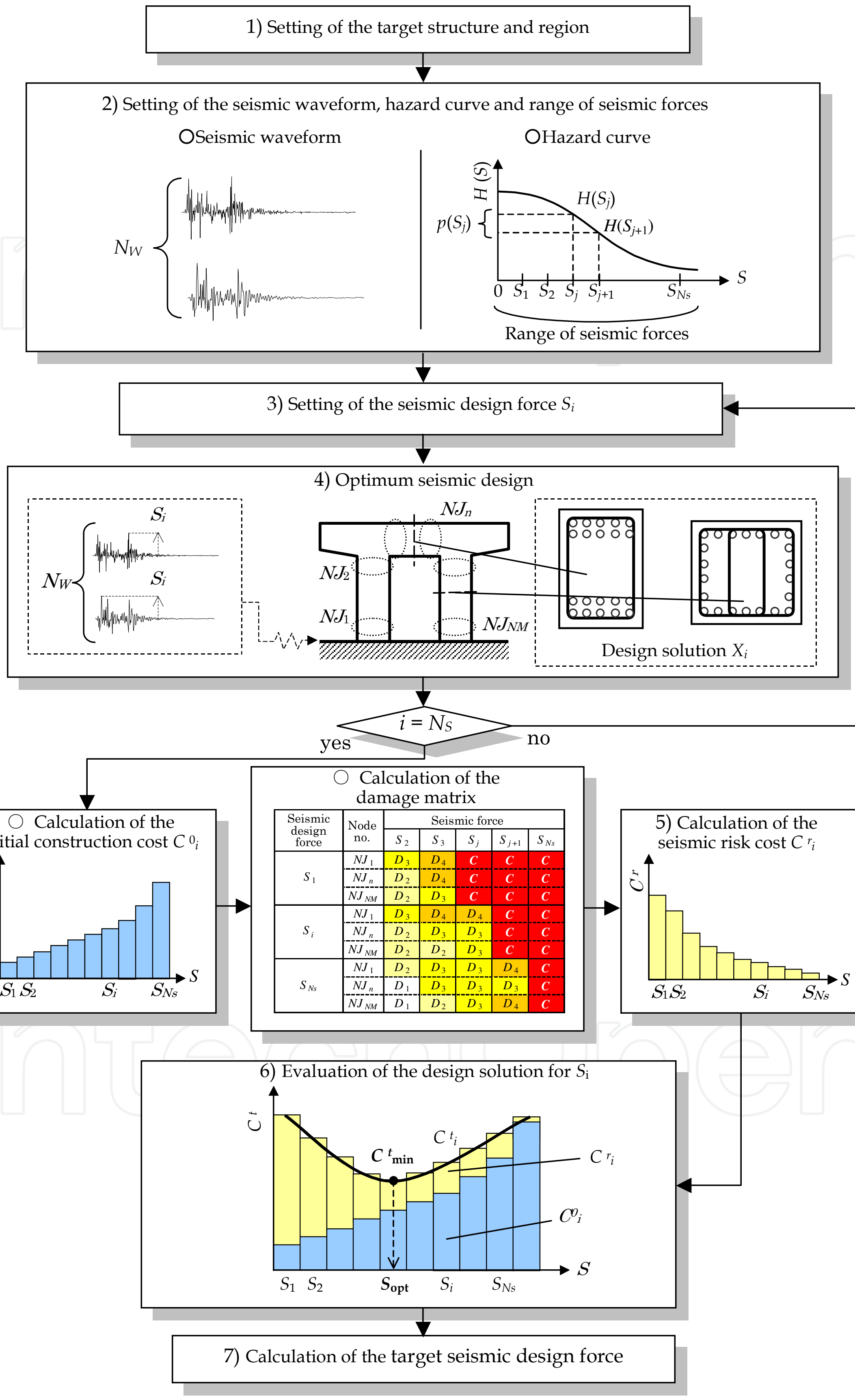

Fig. 1. Flow of calculation of the taqrget seismic design force.

2.2 Setting of the seismic waveform, hazard curve and range of seismic forces

Appropriate seismic waveform and hazard curve are set for the target region. The incremental value ΔS and division number N_S of the seismic forces are also set as shown in Fig. 2.

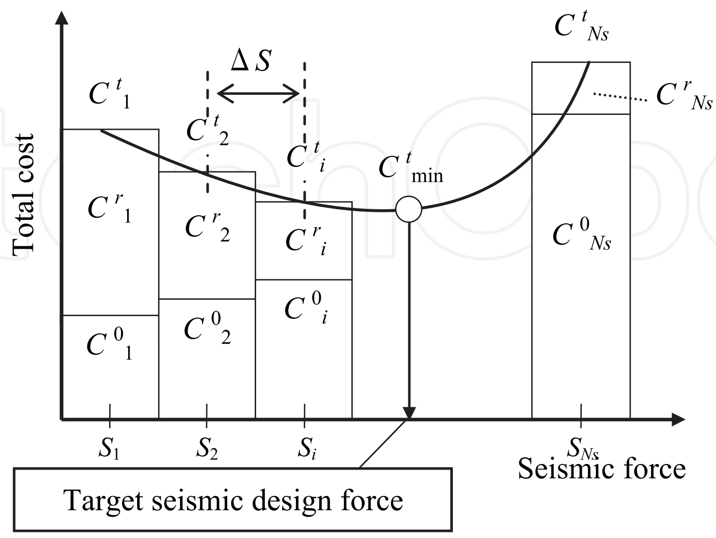

Fig. 2. Relationship between the totalcost and seismic force.

2.3 Setting of the seismic force

Based on the range of seismic forces set in 2), the seismic force for optimum seismic design S_i(i=1~ N_S) is set.

2.4 Optimum seismic design

Optimization of seismic design is performed for each seismic force S_i (i=1~N_S). Details of the formulation of optimum seismic design will be presented later. Time history response analysis is performed by conducting amplitude adjustment to make the maximum amplitude for the seismic waveform set in 2) equal to the seismic force S_i. In this chapter, the optimum solution is calculated through the optimization of the response surface using the RBF network and Genetic Algorithm under the minimized initial construction cost. The initial construction cost of the optimum design solution obtained is presented as C^0_i (i =1~N_s).
In this section, the optimum solution is calculated through the optimum seismic design system of the response surface using the RBF network and Genetic Algorithm by the authors.

2.5 Calculation of the seismic risk cost

The seismic risk cost C^r_i (i =1~N_s) for each design solution found in 4) is calculated for the range of seismic forces set in 2). It means that analysis and verification are performed N_s times for each design solution. The method for calculating the seismic risk cost is as mentioned below.

2.6 Evaluation of the design solution

The design solution for a seismic force S_i is evaluated by the equation below, as the total cost C^t_i (i =1~N_s) found by adding the initial construction cost C^0_i of the design solution found in 4) to the seismic risk cost C^r_i found in 5),

$$C^t_i = C^0_i + C^r_i \tag{1}$$

2.7 Calculation of the target seismic design force

The above calculation is performed to calculate the total cost C^t_i for each S_i. Fig. 2 is a conceptual diagram of the relationship between the total cost C^t_i and seismic force S_i. Of these C^t_i values, the seismic force corresponding to the minimum total cost C^t_{min} is the target seismic design force.

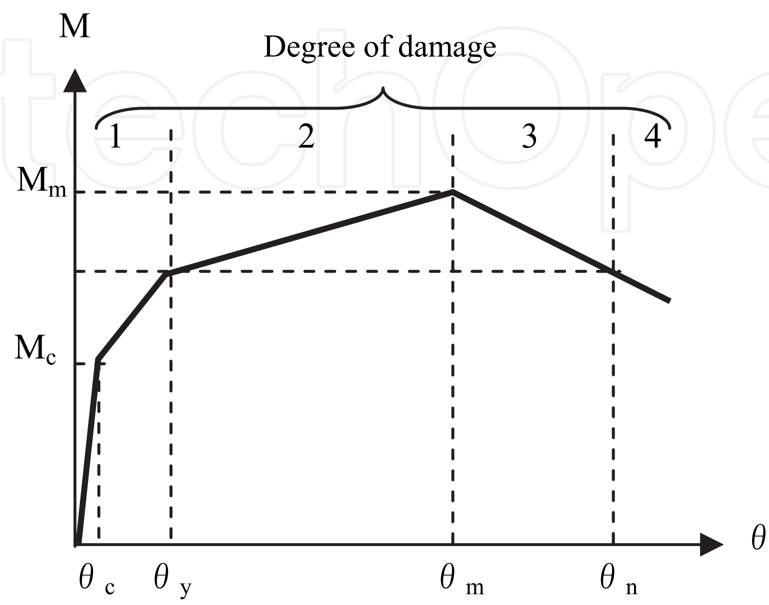

Fig. 3. Skeleton curve and degree of damage.

3. Seismic risk cost

As mentioned before, the total cost for each seismic force is calculated by totalling the initial construction and seismic risk costs. The seismic risk cost is usually calculated using damage and hazard curves. However, a damage matrix is constructed by evaluating damage to all elements where nonlinearity is taken into account instead of using a damage curve, and the seismic risk cost is found by calculating repair and other costs.

This section first defines the damage to an RC structure, and then describes the method for calculating seismic risk costs.

3.1 Definition of damage

In this chapter, damage is defined for all elements where nonlinearity is taken into account. The M-θ relationship of a tetra-linear model, which is represented by the thick black line in Fig. 3, is used as the relationship between the nonlinearity of RC elements and damage , in accordance with the method defined in the Design Code for Railway Structures and instruction manual (seismic design). In the figure, M_c is the bending moment at the time of cracking, M_y is the bending moment at the time of yield, M_m is the maximum bending moment, θ_c is the angle of rotation at the time of cracking, θ_y is the angle of rotation at the time of yield, θ_m is the maximum angle of rotation to maintain M_m, and θ_n is the maximum angle of rotation to maintain M_y.

Classified degree of damage is defined as degree 1 if the maximum response angle of rotation found from time history response analysis is θ_y or smaller, degree 2 if it is θ_m or smaller, degree 3 if it is θ_n or smaller and degree 4 if it exceeds θ_n.

The term "degree 1" represents a condition in which the cracks of concrete member have occurred. The term "degree 2" represents a condition in which the reinforcing bar in the axial direction has yielded. The term "degree 3" represents a condition in which the side of compression of concrete member has fractured. The term "degree 4 "represents a condition in which the flexure capacity has decreased by under the yield capacity.

3.2 Calculation of the damage matrix

To calculate the seismic risk cost, it is necessary to determine the damage of the structure for a certain seismic force and calculate repair and other costs. As mentioned before, this study uses a damage matrix instead of a damage curve, which is generally used to represent the relationship between the seismic force and damage of the structure.

Fig.4 presents the damage matrix using a single-layer portal rigid-frame structure. In the case of a rigid-frame structure, plastic hinges with the effect of nonlinearity are found at 6 sections in total – the upper and lower ends of each column member and the left and right ends of beam members. The table on fig.4 shows the node numbers displayed in the rows and seismic forces in the columns. It is a matrix notation of the damage at each node when various seismic forces are input for a certain design solution. In the table, "C" represents the collapse of the structure. This kind of damage matrix is developed for each of the design solution found for each seismic force.

3.3 Calculation of seismic risk costs

In this chapter, the seismic risk cost is calculated using a damage matrix representing the relationship between the seismic force and damage as shown in fig. 4 and a hazard curve representing the relationship between the seismic force and annual probability of excess as shown in Fig. 5. The seismic risk cost is calculated by the equation below,

$$C^{r}{}_{i} = \sum_{j=1}^{Ns} h(S_j) \cdot c_{ij} \cdot \Delta s(i = 1 \sim N_S) \tag{2}$$

where, $C^{r}{}_{i}$ is the seismic risk cost of the design solution designed for the i-th seismic force, h (S_j) is the annual probability of occurrence found from the hazard curve for the j–th seismic force S_j, c_{ij} is the seismic loss cost for the damage of each element caused by the j-th seismic force when the design solution is designed for the i-th seismic force. While the seismic force S_j is given as a discrete value in this study, the hazard curve shown in Fig. 5 is a continuous function. In this chapter, the annual probability of occurrence is converted into a discrete value by directly using the difference between the annual probabilities of excess corresponding to the seismic forces S_j and S_{j+1}. It will be necessary in the future to study the influence on seismic risks in cases where the annual probability of excess is set with consideration to the range of incremental value ΔS.

While there is the possibility of loss caused by repeated sequence earthquakes, such additional effects will be studied in the future and this chapter limits its focus on the effects of a single earthquake.

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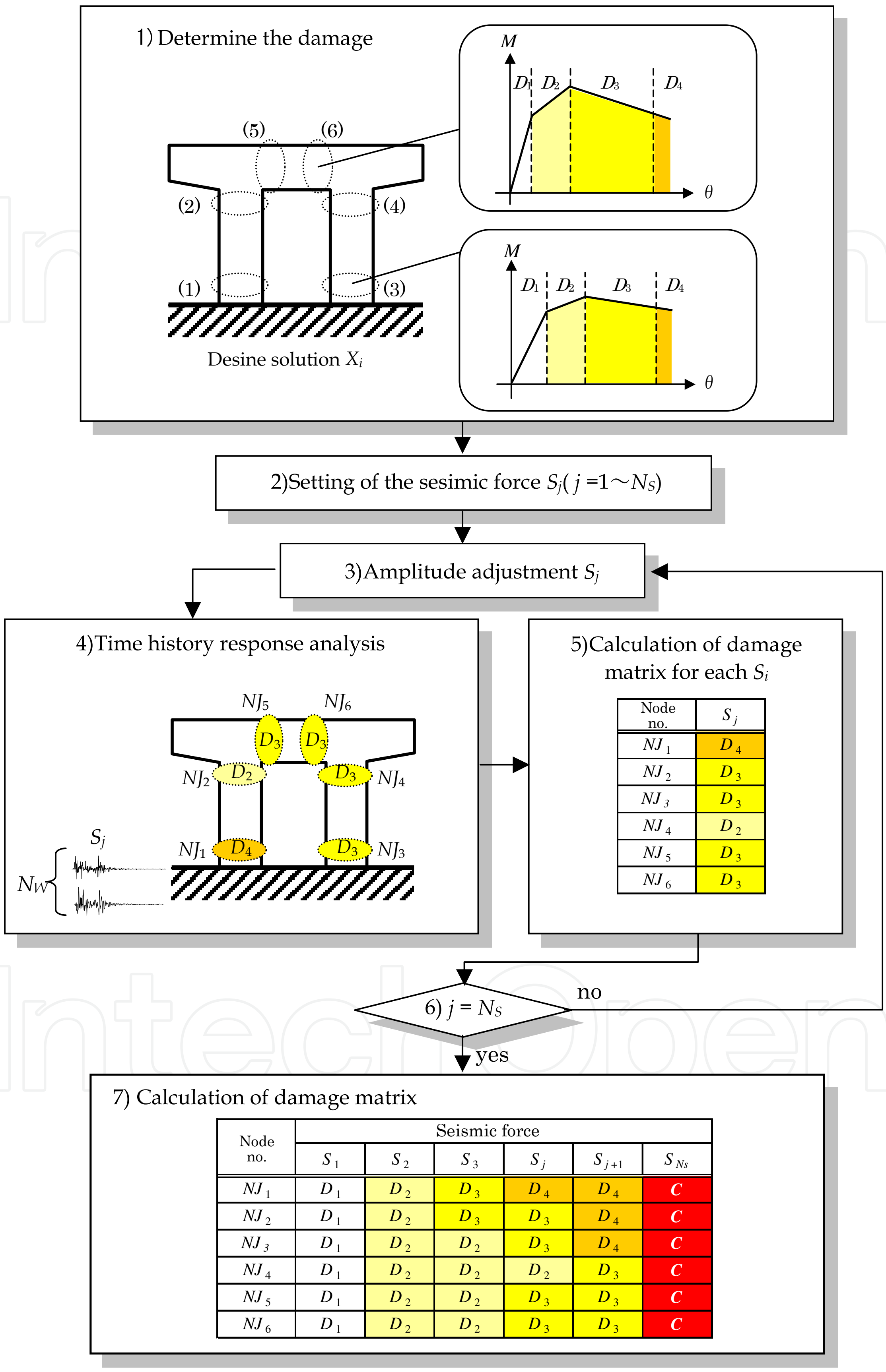

Fig. 4. Flow of the calculation of damage matrix.

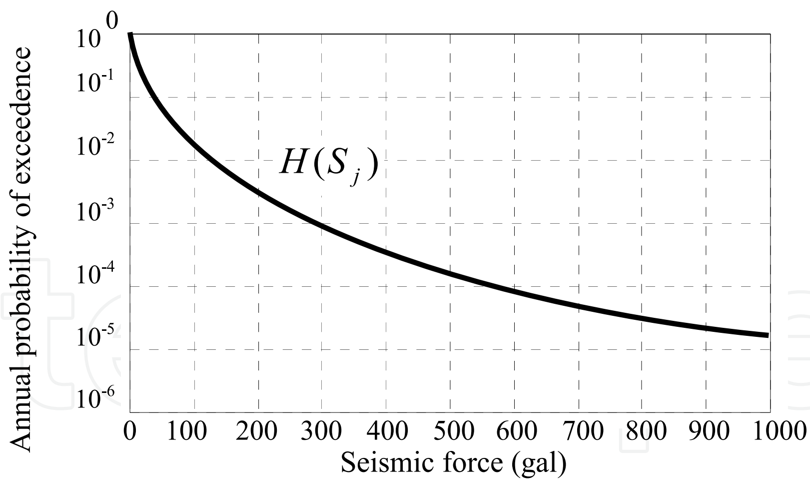

Fig. 5. An example of a hazard curve.

4. Example of the calculation of the target seismic design force

In this chapter, the target seismic design force of an RC rigid-frame railway viaduct is calculated. The optimum design problem and examples of numerical calculation will be presented below.

4.1 Optimum design problem

A standard single-layer RC rigid-frame railway viaduct with a spread foundation shown in Fig. 6 is used for calculation example. Non-linearity is taken into account for the columns and beam members.

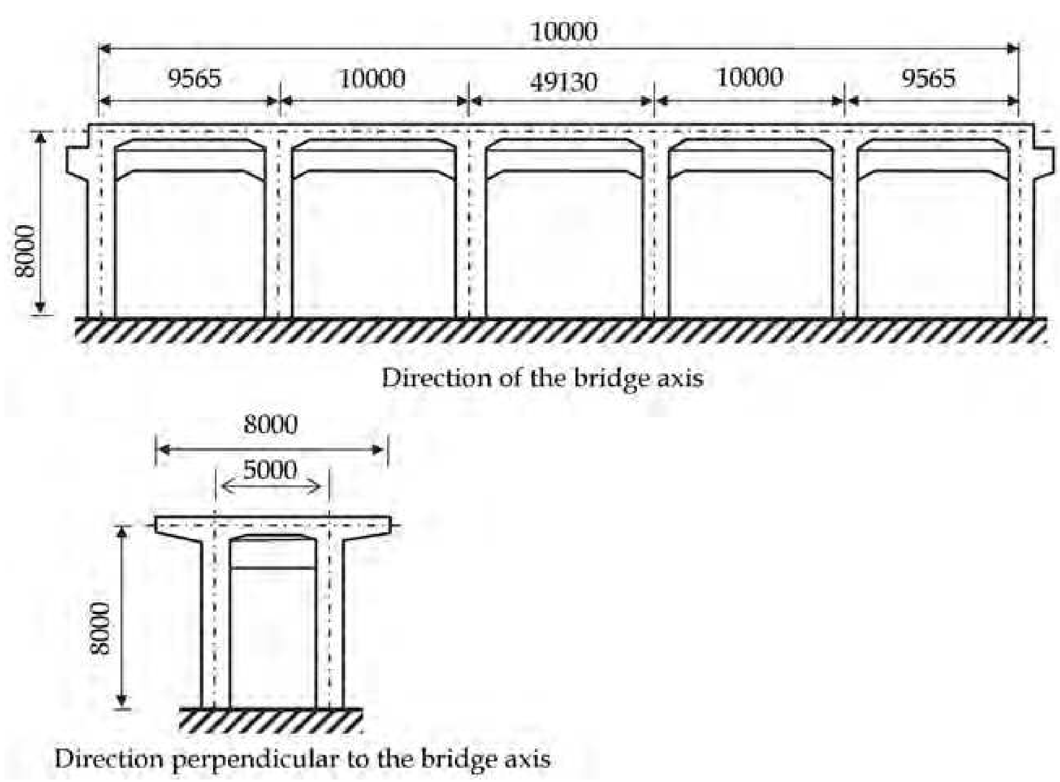

Fig. 6. Structural model.

In the optimum design for a certain seismic force S_i, the initial construction cost, which is the total of the costs related to concrete and reinforcement, is used as the objective function. The objective function is calculated by the equation below

$$OBJ = C_i^{\,o} = C^c + C^s \rightarrow \min \tag{3}$$

where, C^c is the concrete-related cost (unit) and C^s is the reinforcement-related cost (unit). They are calculated by the equations (4) and (5), respectively,

$$C^C = \alpha^c \cdot V^c \cdot K^c \tag{4}$$

$$C^S = \alpha^s \cdot V^s \cdot K^s \cdot G^s \tag{5}$$

where, α_c is the unit correction factor of concrete, V_c is the amount of concrete (m^3), K_c is the cost per unit volume of concrete (=65.1unit/m^3), α_s is the unit correction factor of reinforcement, V_s is the amount of reinforcement (m^3), K_s is the cost per unit weight of reinforcement (= 9.1unit/kN) and G_s is the unit weight of reinforcement (=77kN/m^3). In this study, α_c and α_s are both set as 1.0. The cost per unit volume of concrete and the cost per unit weight of reinforcement are found through conversion from the construction cost, including material cost, cost for scaffolding and personnel cost.
Constraints are found for the verifiability of the angle of rotation and shear force against the seismic force S_i, and are calculated by the equation below,

$$g^r{}_{Jk} = \frac{\theta^d{}_{Jk}}{\theta^m{}_{Jk}} - 1 \le 0 \, (J = 1 \sim N_m \, , \, k = 1 \sim 2) \tag{6}$$

$$g^{SD}{}_J = \frac{V^d{}_J}{V^{rd}{}_J} - 1 \le 0 \qquad (= 1 \sim N_m) \tag{7}$$

where, $g^r{}_{Jk}$ is the angle of rotation, $g^{SD}{}_J$ is the constraint related to shear force, $\theta^d{}_{Jk}$ is the maximum response angle of rotation at the end k of the member J, $\theta^m{}_{Jk}$ is the maximum angle of rotation with which M_m on the skeleton curve of the end k of the member J can be maintained, $V^d{}_J$ is the maximum response shear force of the element J, $V^{rd}{}_J$ is the permissible shear force of the member J and N_m is the number of members.
The subjects of design are column and beam members. The cross sections of column members are square and those of beam members are rectangular. There are 7 design variables in total -- the section width B, section height H, number of reinforcing bars in the axial direction N, number of rows of reinforcing bars in the axial direction J_N, diameter of reinforcing bars in the axial direction D, placing of shear reinforcement N_W and spacing of shear reinforcement S_V .
Figs. 7 and 8 display the section specifications and arrangement of shear reinforcement, respectively. The spacing of shear reinforcement in section 2H of Fig. 8 is 100 mm.
Table 1. lists the potential values of design variables. By setting the minimum spacing of reinforcement as the diameter of reinforcement D × 2.5 (mm) and the maximum spacing of reinforcement as 250 mm, the maximum and minimum numbers of reinforcing bars, which are obtained based on the section width and diameter of reinforcing bars, are divided by 8 to find the design variable of the number of reinforcing bars in the axial direction N.

As materials, concrete with a design standard strength of 24N/mm² and SD345 reinforcement are used.

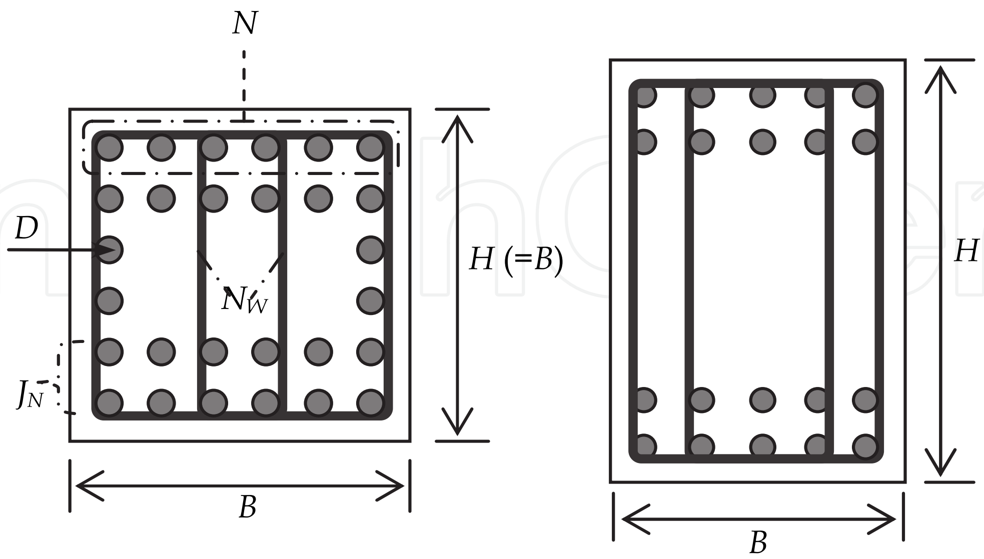

Fig. 7. Details of dimensions and reinforcement for x-sections of columns and beams.

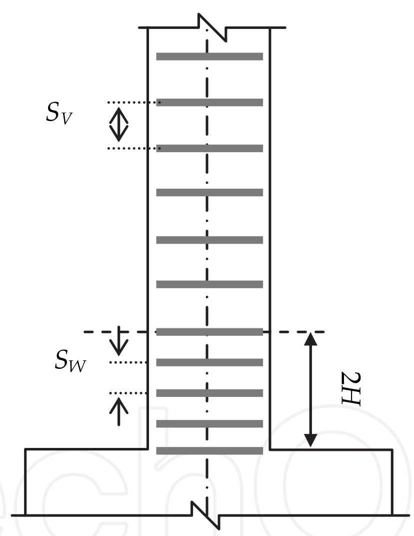

Fig. 8. Details of arrangement of shear reinforcement.

B (mm)	500～1200 (100mm intervals)
H (mm)	B + 200～800 (100mm intervals)
N	8 types depending on B and H
J_N	1 or 2
D (mm)	19 or 25 or 29 or 32
N_W	1～4
S_V (mm)	100 or 200

Table 1. Potential values of design variables.

4.2 Seismic loss cost

The repair cost for damage is used as the seismic loss cost. The seismic loss cost is calculated by the equation below,

$$c_{ij} = \sum_{J=1}^{N_m} c^{rep}{}_{ijJ} \; (i = 1 \sim N_S, j = 1 \sim N_S) \tag{8}$$

where, c_{ij} is the seismic loss cost for the damage of members caused by the j-th seismic force in a design solution designed for the i-th seismic force, and $c^{rep}{}_{ijJ}$ is the repair cost for the member J damaged by the j-th seismic force in a design solution designed for the i-th seismic force. The repair cost is determined depending on the repair method applicable to the considered section. In this chapter, different repair methods are adopted for the lower and upper ends of column members and upper beam sections.

Table 2. presents the damage conditions and repair methods corresponding to the damage of different members. Table 3. presents the calculation formulas of repair cost corresponding to the repair methods. Fig. 9 illustrates the calculation model of repair cost.

Degree of damage	Damage condition	Repair method		
		Culumn(upper end)	Culumn(lower end)	Upper beam
1	Slight bending cracking	None	None	None
2	Yield of reinforcement in the axial direction Bending and shear cracking	Scaffolding Grouting of cracks	Excavation Grouting of cracks	Scaffolding Grouting of cracks
3	Flaking of concrete cover Buckling of reinforcement in the axial direction	Scaffolding Grouting of cracks Adjustment of reinforcement Repair of concrete cover	Excavation Grouting of cracks Adjustment of reinforcement Repair of concrete cover	Track removal Scaffolding Grouting of cracks Adjustment of reinforcement Repair of concrete cover Bridge-deck waterproofing Track restoration
4	Damage of internal concrete Break of reinforcement in the axial direction Break of lateral ties	Temporary support of slab Scaffolding Concrete removal Replacement of reinforcement Concrete placement	Temporary support of slab Excavation Concrete removal Replacement of reinforcement Backfilling	Temporary support of slab Track removal Scaffolding Concrete removal Replacement of reinforcement Concrete placement Bridge-deck waterproofing Track restoration

Table 2. Damage conditions and repair methods.

(1) Culumn(upper end)

Degree of damage	Repair method		Unit	Unit price	Calculation formula
1	None		-	-	- - - - -
2	Scaffolding		m^2	2,380	$\{(H+0.914\times2+0.4\times2)\times2+(H+0.4\times2)\times2\}\times2\times H1$
	Grouting of cracks		ℓ	5,500	$(H\times B\times H)\times2\times10$
3	Scaffolding		m^2	2,380	$\{(H+0.914\times2+0.4\times2)\times2+(H+0.4\times2)\times2\}\times2\times H1$
	Grouting of cracks		ℓ	5,500	$(H\times B\times H\times H)\times2\times10$
	Repair of concrete cover	1	m^3	22,410	$(H\times B\times H)\times2\times0.35$
		2	m^2	7,090	$(H\times H)\times4\times2$
4	Temporary support of slab		m^3	4,680	$10\times(B2+H)\times H$
	Scaffolding		m^2	2,380	$\{(H+0.914\times2+0.4\times2)\times2+(H+0.4\times2)\times2\}\times2\times H1$
	Concrete removal		m^3	32,000	$(H\times B\times H)\times2$
	Replacement of reinforcement	1	kg	120	$7850\times A_{SD}\times(H\times1.5)\times((N-1)\times4+2\times(N-2)\times(J_N-1)) + 7850\times A_{SD}\times N_W\times2\times((1+0.4\times(NW-1))\times(B-2\times0.04-D)+N_W\times(H-2\times0.04-D))$
		2		2,700	$4\times(N-1)+2\times(N-2)\times(J_N-1)+N_W$
	Concrete placement	1	m^3	22,410	$(H\times B\times H)\times2$
		2	m^2	7,090	$(H\times H)\times4\times2$

(2) Culumn(lower end)

Degree of damage	Repair method		Unit	Unit price	Calculation formula
1	None		-	-	- - - - -
2	Excavation		m^3	6,720	$\{(H+2)2-H2\}\times0.5\times2$
	Grouting of cracks		ℓ	5,500	$(H\times B\times H)\times2\times10$
	Backfilling		m^3	1,112	$\{(H+2)2-H2)\times0.5\times2$
3	Excavation		m^3	6,720	$\{(H+2)2-H2\}\times0.5\times2$
	Grouting of cracks		ℓ	5,500	$(H\times B\times H)\times2\times25$
	Repair of concrete cover	1	m^3	22,410	$(H\times B\times H)\times2\times0.35$
		2	m^2	7,090	$(H\times H)\times4\times2$
	Backfilling		m^3	1,112	$\{(H+2)2-H2)\times0.5\times2$
4	Temporary support of slab		m^3	4,680	$L1\times(B2+H)\times H$
	Excavation		m^3	6,720	$\{(H+2)2-H2\}\times0.5\times2$
	Concrete removal		m^3	32,000	$(H\times B\times H)\times2$
	Replacement of reinforcement	1	kg	120	$7850\times A_{SD}\times(H\times1.5)\times((N-1)\times4+2\times(N-2)\times(J_N-1)) + 7850\times A_{SD}\times N_W\times2\times((1+0.4\times(NW-1))\times(B-2\times0.04-D)+N_W\times(H-2\times0.04-D))$
		2		2,700	$4\times(N-1)+2\times(N-2)\times(J_N-1)+N_W$
	Repair of concrete cover	1	m^3	22,410	$(H\times B\times H)\times2$
		2	m^2	7,090	$(H\times B\times H)\times4\times2$
	Backfilling		m^3	1,112	$\{(H+2)2-H2)\times0.5\times2$

(3) Upper beam

Degree of damage	Repair method		Unit	Unit price	Calculation formula
1	None		-	-	- - - - -
2	Scaffolding		m^2	2,380	$(B\times2+B\times2)\times H1$
	Grouting of cracks		ℓ	5,500	$(H\times B\times H)\times2\times10$
3	Track removal		m	50,000	$L1\times2$
	Scaffolding		m^2	2,380	$(B\times2+B\times2)\times H1$
	Grouting of cracks		ℓ	5,500	$(H\times B\times H)\times2\times25$
	Repair of concrete cover	1	m^3	22,410	$(H\times B\times H)\times2\times0.35$
		2	m^2	7,090	$\{(H-0.3)\times H\times2+(H\times B)\}\times2$
	Bridge-deck waterproofing		m^2	20,000	$B1\times L1$
	Track restoration		m	150,000	$L1\times2$
4	Temporary support of slab		m^3	4,680	$L1\times(B2+H)\times H$
	Track removal		m	50,000	$L1\times2$
	Scaffolding		m^2	2,380	$(B\times2+B\times2)\times H1$
	Concrete removal		m^3	32,000	$(h1\times B\times h1)\times2$
	Replacement of reinforcement	1	kg	120	$7850\times A_{SD}{}^{*}\times(H\times1.5)\times((N-1)\times4+2\times(N-2)\times(J_N-1)) + 7850\times A_{SD}\times N_W\times2\times((1+0.4\times(NW-1))\times(B-2\times0.04-D)+N_W\times(H-2\times0.04-D))$
		2		2,700	$N\times J_N\times2+N_W$
	Concrete placement	1	m^3	22,410	$(H\times B\times H)\times2$
		2	m^2	7,090	$\{(H-0.3)\times H\times2+(H\times B)\}\times2$
	Bridge-deck waterproofing		m^2	20,000	$B1\times L1$
	Track restoration		m	150,000	$L1\times2$

Table 3. Calculation formulas of repair cost.

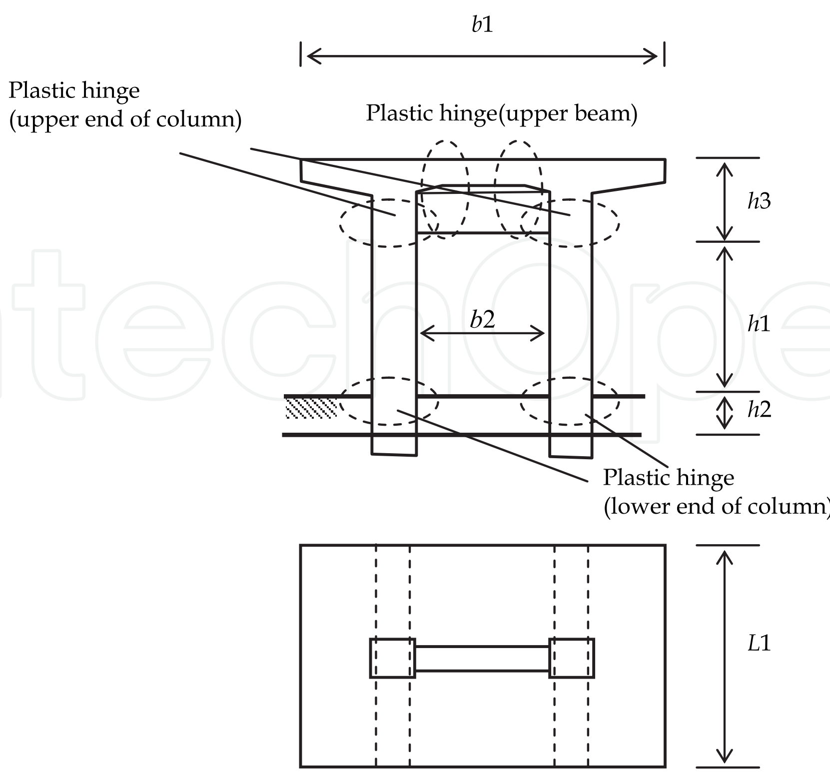

Fig. 9. Calculation model of repair cost.

If the lower ends of all the column members exceed the ultimate angle of rotation, it means that the structure has collapsed and the reconstruction cost replaces the repair cost, which is supposed to be 1.5 times the initial construction cost.

While this definition is based on bending fracture-type collapse, it is also necessary to take the shear fracture-type collapse of structures into account. However, since the seismic force causing bending fracture could be calculated using the damage matrix in this method, it is considered possible to perform analysis based on bending fracture-type collapse by the placement of shear reinforcement, which is not subject to shear fracture caused by the seismic force.

The acceleration waveform of an inland-type earthquake with Level 2 earthquake motion displayed in Fig. 10 is used as the input earthquake motion for time history response analysis and the calculation of the seismic risk cost, and 3 hazard curves (0.16, 0.50 and 0.84 in fractile) displayed in Fig. 11 are adopted.

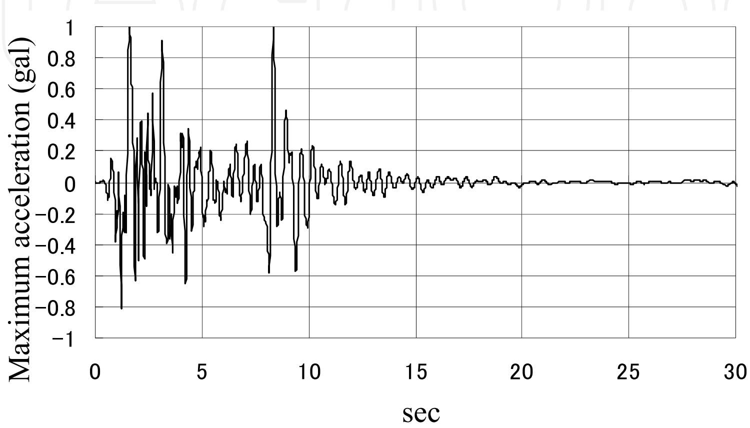

Fig. 10. Acceleration waveform.

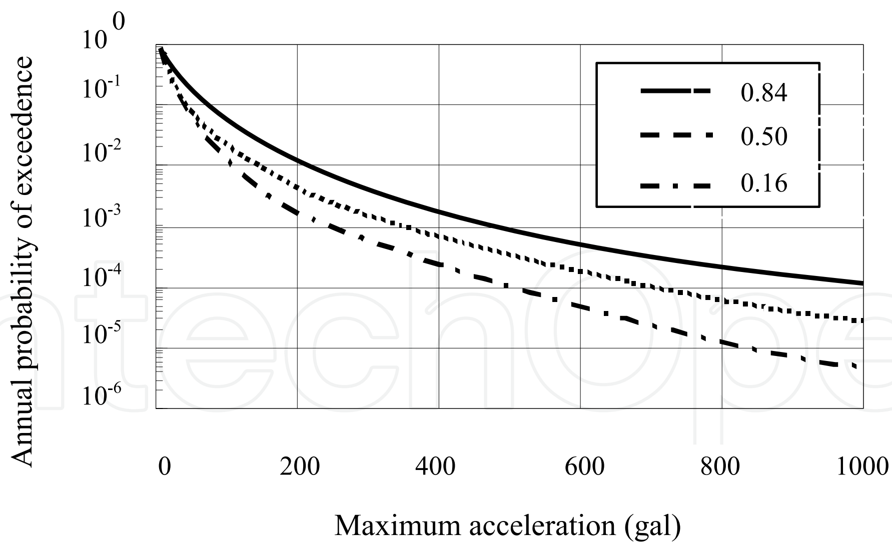

Fig. 11. Hazard curves.

4.3 Numerical results

The calculation results for the RC rigid-frame viaduct are presented. The calculation is performed for seismic forces of 50 to 1,000 gal on the assumption that the dividing width ΔS is 50 gal and the dividing number Ns is 20 for the seismic forces. Since the incremental value of design acceleration must be set taking the influence on design solutions into account, the value in this study is set as 50 gal, which is small enough not to have a significant influence on design solutions. The incremental value of design acceleration can be even smaller if necessary.

Table 4. lists the design solutions found for various seismic forces. In the table, N_P and N_B represent the numbers of reinforcing bars in the column and beam sections, respectively. Fig. 12 displays the relationship between the seismic force and initial construction cost. In the figure, the symbol ■ represents the initial construction cost.

When the seismic force is within the range of 50 to 400 gal, the initial construction cost is uniform. These are the design solutions with which the objective function becomes minimum by a combination of preset design variables. The initial construction cost tends to increase with increasing seismic force in design solutions of 400 gal or greater. The initial construction cost sharply increases between 750 and 800 gal. As shown in Table 4, this is because the design variables of the two design solutions, B = 900 mm and H = 1,200 mm of H, are necessary when the seismic force is 800 gal, while the seismic performance is satisfied with B = 600 mm and H = 800 mm at 50 gal.

Next, Table 5. presents the damage matrix of design solutions found for various seismic forces (Table 4.). The table shows the seismic forces in rows and input seismic forces for calculation of the damage matrix in columns. The structural model used has nonlinear performance at a total of 28 sections -- 22 in the direction of the bridge axis and 6 in the direction perpendicular to the bridge axis. Although damage is calculated for all members, the maximum values for columns and beams in two directions are presented for each design solution since it is difficult to display all the calculation results. In the table, P_I is the column member in the direction of the bridge axis, P_O is the column member in the direction perpendicular to the bridge axis, B_I is the beam member in the direction of the bridge axis, and B_O is the beam member in the direction perpendicular to the bridge axis. The right side of the thick line represents the cases where the input seismic force exceeds the value used for design.

Si (gal)	*B* (mm)	*H* (mm)	N_P	N_B	J_N	*D* (mm)	N_W	S_V (mm)	*OBJ* (C^0_i) (unit ×10^3)
50	500	700	3	5	1	22	1	200	6940
100	500	700	3	5	1	22	1	200	6940
150	500	700	3	5	1	22	1	200	6940
200	500	700	3	5	1	22	1	200	6940
250	500	700	3	5	1	22	1	200	6940
300	500	700	3	5	1	22	1	200	6940
350	500	700	3	5	1	25	1	200	6940
400	500	700	3	5	1	22	1	200	6940
450	500	700	4	6	1	22	1	200	7219
500	500	700	3	5	1	22	2	200	7389
550	500	700	3	5	1	25	2	200	7610
600	500	700	6	10	2	22	2	100	9646
650	600	800	4	6	1	22	2	200	10193
700	600	800	4	6	1	22	2	200	10193
750	600	800	5	7	2	25	2	100	12000
800	900	1200	16	23	1	22	2	200	24635
850	1000	1200	15	19	1	22	2	200	26833
900	1000	1200	16	21	1	22	2	200	27189
950	1000	1200	10	12	1	32	2	200	28087
1000	1100	1300	19	23	1	22	2	200	31852

Table 4. Design solution by seismic force (Si).

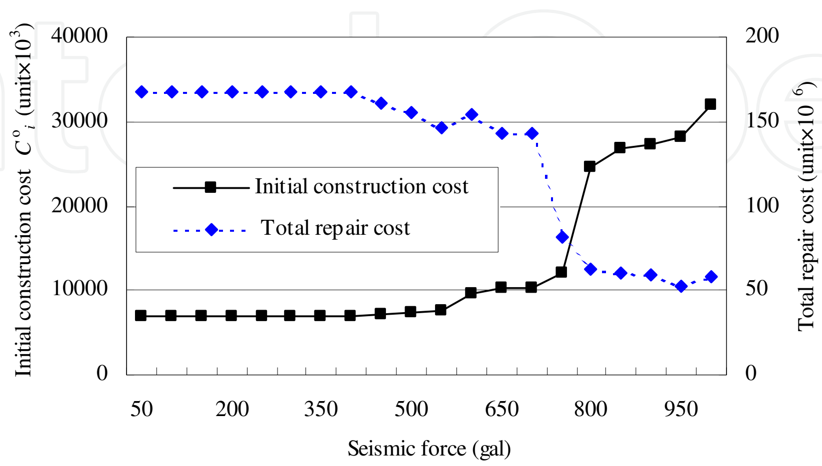

Fig. 12. Initial construction cost and total repair costby seismic force.

Seismic design force (gal)	member	Input seismic force (gal)																			
		50	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800	850	900	950	1000
50	P_I	1	1	2	2	2	2	2	2	2	4	c	c	c	c	c	c	c	c	c	c
	B_i	1	1	1	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c	c
	P_O	1	1	1	2	2	2	2	2	3	c	c	c	c	c	c	c	c	c	c	c
	B_O	1	1	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c	c	c
100	P_I	1	1	2	2	2	2	2	2	2	4	c	c	c	c	c	c	c	c	c	c
	B_i	1	1	1	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c	c
	P_O	1	1	1	2	2	2	2	2	3	c	c	c	c	c	c	c	c	c	c	c
	B_O	1	1	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c	c	c
150	P_I	1	1	2	2	2	2	2	2	2	4	c	c	c	c	c	c	c	c	c	c
	B_i	1	1	1	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c	c
	P_O	1	1	1	2	2	2	2	2	3	c	c	c	c	c	c	c	c	c	c	c
	B_O	1	1	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c	c	c
200	P_I	1	1	2	2	2	2	2	2	2	4	c	c	c	c	c	c	c	c	c	c
	B_i	1	1	1	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c	c
	P_O	1	1	1	2	2	2	2	2	3	c	c	c	c	c	c	c	c	c	c	c
	B_O	1	1	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c	c	c
250	P_I	1	1	2	2	2	2	2	2	2	4	c	c	c	c	c	c	c	c	c	c
	B_i	1	1	1	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c	c
	P_O	1	1	1	2	2	2	2	2	3	c	c	c	c	c	c	c	c	c	c	c
	B_O	1	1	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c	c	c
300	P_I	1	1	2	2	2	2	2	2	2	4	c	c	c	c	c	c	c	c	c	c
	B_i	1	1	1	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c	c
	P_O	1	1	1	2	2	2	2	2	3	c	c	c	c	c	c	c	c	c	c	c
	B_O	1	1	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c	c	c
350	P_I	1	1	2	2	2	2	2	2	2	4	c	c	c	c	c	c	c	c	c	c
	B_i	1	1	1	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c	c
	P_O	1	1	1	2	2	2	2	2	3	c	c	c	c	c	c	c	c	c	c	c
	B_O	1	1	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c	c	c
400	P_I	1	1	2	2	2	2	2	2	2	4	c	c	c	c	c	c	c	c	c	c
	B_i	1	1	1	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c	c
	P_O	1	1	1	2	2	2	2	2	3	c	c	c	c	c	c	c	c	c	c	c
	B_O	1	1	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c	c	c
450	P_I	1	1	1	2	2	2	2	2	2	3	4	c	c	c	c	c	c	c	c	c
	B_i	1	1	1	2	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c
	P_O	1	1	1	2	2	2	2	2	2	3	c	c	c	c	c	c	c	c	c	c
	B_O	1	1	1	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c	c
500	P_I	1	1	2	2	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c
	B_i	1	1	1	2	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c
	P_O	1	1	1	2	2	2	2	2	2	2	3	c	c	c	c	c	c	c	c	c
	B_O	1	1	2	2	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c
550	P_I	1	1	1	2	2	2	2	2	2	2	2	3	c	c	c	c	c	c	c	c
	B_i	1	1	1	1	2	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c
	P_O	1	1	1	2	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c
	B_O	1	1	1	2	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c	c
600	P_I	1	1	1	2	2	2	2	2	2	2	2	2	3	c	c	c	c	c	c	c
	B_i	1	1	1	1	1	1	1	1	1	1	1	1	1	c	c	c	c	c	c	c
	P_O	1	1	1	2	2	2	2	2	2	2	2	2	c	c	c	c	c	c	c	c
	B_O	1	1	1	1	1	1	1	1	1	1	1	1	c	c	c	c	c	c	c	c
650	P_I	1	1	2	2	2	2	2	2	2	2	2	2	2	2	3	c	c	c	c	c
	B_i	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	c	c	c	c	c
	P_O	1	1	2	2	2	2	2	2	2	2	2	2	2	2	c	c	c	c	c	c
	B_O	1	1	2	2	2	2	2	2	2	2	2	2	2	2	c	c	c	c	c	c
700	P_I	1	1	2	2	2	2	2	2	2	2	2	2	2	2	3	c	c	c	c	c
	B_i	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	c	c	c	c	c
	P_O	1	1	2	2	2	2	2	2	2	2	2	2	2	2	c	c	c	c	c	c
	B_O	1	1	2	2	2	2	2	2	2	2	2	2	2	2	c	c	c	c	c	c
750	P_I	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	c	c
	B_i	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	c	c
	P_O	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	c	c	c
	B_O	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	c	c	c
800	P_I	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3
	B_i	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	P_O	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	c
	B_O	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	c
850	P_I	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3
	B_i	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2
	P_O	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3
	B_O	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2
900	P_I	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3
	B_i	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2
	P_O	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3
	B_O	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2
950	P_I	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	3
	B_i	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2
	P_O	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3
	B_O	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2
1000	P_I	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	B_i	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2
	P_O	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	B_O	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2

No damage —— Degree of damage → Collapse

1	2	3	4	c

Table 5. Damage matrix.

Damage is examined for design solutions at 400 gal or more, with which the initial construction cost became the minimum. In design solutions between 400 gal and 800 gal, where the objective function increases sharply, collapse in the direction perpendicular to the bridge axis occurred with a seismic force 50 to 150 gal stronger than the seismic force used for design, while collapse in the direction of the bridge axis occurred with a seismic force 100 to 200 gal stronger. It can thus be seen that the seismic performance in the direction perpendicular to the bridge axis is lower than that in the direction of the bridge axis when the seismic force is stronger than that used for design. In design solutions at 800 gal or more, on the other hand, collapse does not occur even with a seismic force of 1,000 gal.

Next, the symbol ◆ in Fig. 12 represent the total repair cost for each design solution calculated from the damage matrix in Table 5. The total repair cost is found by totalling the repair costs for all the seismic forces (columns in Table 5.) between 50 and 1,000 gal for each design solution. The total repair cost of each design solution tends to be in inverse proportion to the initial construction cost. The difference in total repair cost is small although the initial construction cost of the design solution at 750 gal is almost double that of the design solution at 800 gal. This is because the damage level of the beam member using the design solution at 800 gal is 2 at 350 gal, while the beam member using the design solution at 750 gal is undamaged until the seismic force reached 800 gal. Since the repair of beam members requires scaffolding and other works even if damage is minor, the repair cost is higher compared with that for column members. Also, since collapse would not occur even with a seismic force of 1,000 gal in the case of a design solution for a seismic force of 800 gal or more, the total repair cost is approximately half of that for other design solutions with collapse, except for that at 750 gal.

Figs. 13 to 15 display the relationship between the total cost and seismic force in the case where the repair cost for each design solution, which is calculated using the hazard curve in Fig. 11 and based on the damage matrix in Table 5. , is used as the seismic risk cost. In the figures, the horizontal and vertical axes represent the seismic force and total cost and the white and blue parts indicate the initial construction cost and seismic risk cost, respectively. Each figure presents the results for a 0.16, 0.50 or 0.84 fractile hazard curve. The arrow in each figure indicates the section where the total cost is the lowest, or the target seismic design force.

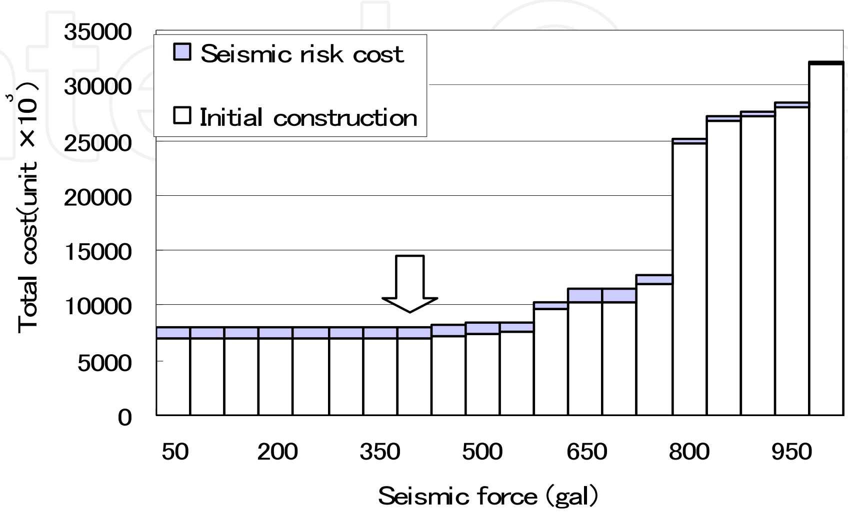

Fig. 13. Relationship between the total cost and seismic force (0.16 fractile hazard curve) .

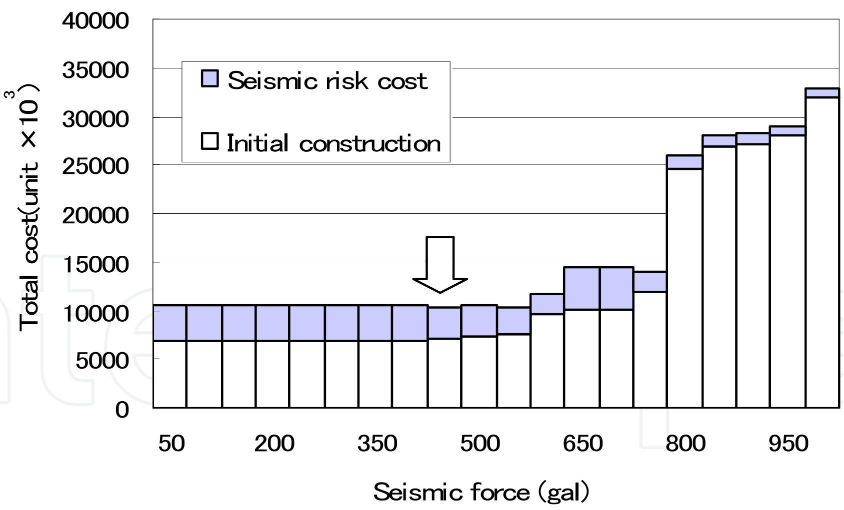

Fig. 14. Relationship between the total cost and seismic force (0.50 fractile hazard curve).

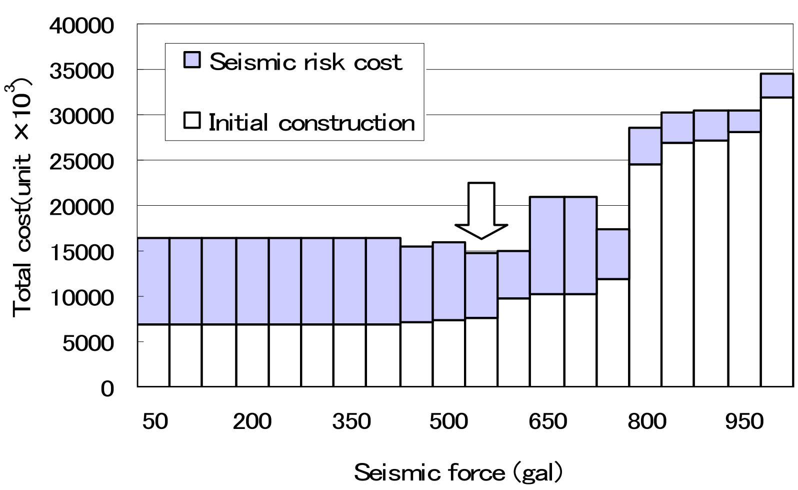

Fig. 15. Relationship between the total cost and seismic force (0.84 fractile hazard curve) .

The target seismic design force is 400, 450 and 550 gal for 0.16, 0.50 and 0.84 fractile hazard curves, respectively. It is confirmed that, even with the same structural model, the target seismic design forces would vary with differences in the occurrence probability of earthquakes. In the relationship between the total cost and seismic force in 0.50 and 0.85 fractile hazard curves, the total cost at 750 gal is locally low. This is because the seismic risks are extremely high at 650 and 700 gal. It can be seen from the damage matrix that damage to beam members started at 150 gal in design solutions designed for 650 and 700 gal. Because the seismic force causing damage is lower compared with other design solutions and the repair cost for beam members is higher, the estimated seismic risk became higher. As a result, the total cost at 750 gal is locally low.

5. Conclusion

The current seismic design criteria are based on the verification of seismic performance using Level-1 and -2 seismic forces. However, since earthquake motions that are stronger than Level 1 but do not exceed Level 2 may be generated through time during the service

life of a structure in reality. Against such a background, this chapter examined target seismic design forces taking seismic risks into account as an attempt to apply seismic risk management to seismic design methods.
The results obtained in this chapter are as listed below.

1. A method for calculating seismic forces with which the total cost can be minimized is presented. The proposed method has the following characteristics:

- The total cost is the total of the initial construction and seismic risk costs. The seismic risk cost includes the costs associated with the damage and collapse of structures.
- The damage of members is calculated by using the nonlinear characteristics related to the damage of members.
- To find the damage and collapse processes of structures, a damage matrix based on the damage conditions of all members with nonlinearity is used to reflect the influence of the repair cost depending on differences in structural type and damage conditions as precisely as possible.

2. The proposed method for calculating target seismic design forces is applied to RC rigid-frame railway viaduct. As a result of calculation using three hazard curves with different fractile values, the following knowledge is obtained:

- In calculation example, the target seismic design forces vary with difference in the occurrence probability of earthquakes. When the probability is higher, the target forces also become higher.

A method is presented for the calculation of target seismic design forces, for which the seismic risks of damage and collapse caused by various seismic forces are taken into account. By applying hazard curves unique to this region and seismic waveforms taking regional ground and other properties closely into account to the method presented in this study, the target seismic design force with minimum total cost including seismic risk can be found from the occurrence probability of earthquakes in the target region and damage unique to the target structure. While social consensus based on the accumulation of this kind of study is necessary for the setting of seismic forces to use in seismic design, the authors will be pleased if these studies serve as references for future studies of seismic forces in seismic design.

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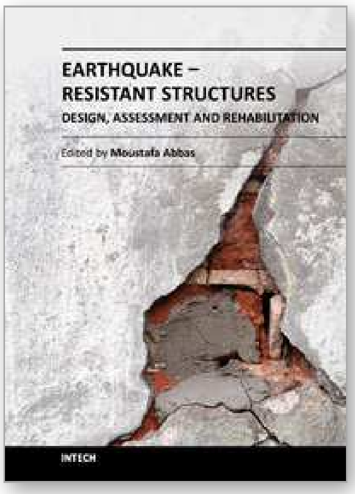

Earthquake-Resistant Structures - Design, Assessment and Rehabilitation
Edited by Prof. Abbas Moustafa

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This book deals with earthquake-resistant structures, such as, buildings, bridges and liquid storage tanks. It contains twenty chapters covering several interesting research topics written by researchers and experts in the field of earthquake engineering. The book covers seismic-resistance design of masonry and reinforced concrete structures to be constructed as well as safety assessment, strengthening and rehabilitation of existing structures against earthquake loads. It also includes three chapters on electromagnetic sensing techniques for health assessment of structures, post earthquake assessment of steel buildings in fire environment and response of underground pipes to blast loads. The book provides the state-of-the-art on recent progress in earthquake-resistant structures. It should be useful to graduate students, researchers and practicing structural engineers.

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