A STUDY ON CALCULATION OF SEISMIC DESIGN FORCES FOR STRUCTURES CONSIDERING THEIR SEISMIC RISKS

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Considering the seismic risks associated with structural damage and loss caused by various seismic forces, the total cost cannot necessarily be minimized by the verification of seismic performance using two levels of seismic forces (Levels 1 and 2 earthquake motion). Here, the total cost is defined as the summation of the initial construction cost and the seismic risk cost, which includes repair and user costs. The seismic force, with which the total cost becomes the minimum, is thought to vary with the function and type of the structure to be designed. From such a point of view, this paper presents a method for determining the target seismic design force unique to the intended structure.

Key Words: seismic design force, structural optimization, seismic risk, RC structures, user cost

1. INTRODUCTION

The Japanese seismic design criteria for road and railway bridges\textsuperscript{1,2} 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\textsuperscript{3,4}. 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 repairability or collapse of a structure subject to Level 1 or 2 earthquake motions based on the current seismic design force. This has
been pointed out as a problem of the currently adopted two-level seismic design method

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. Ito and Wada conducted a study to include the seismic risk of the damage or collapse of a single column RC pier caused by various seismic forces in the life-cycle assessment of the structure. Also, Sato et al. calculated the seismic risk of an actual group of bridges and applied the results to a reinforcement plan.

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. For example, even if the top horizontal displacement, or damage, is identical for a certain earthquake motion, the repair method differs greatly in cases where the plastic deformation are observed at the bases of columns from cases where they are observed in both columns and beams. Considering also the possibility of the plastic deformations of underground beams and pile foundations, it is not appropriate to define the damage to a structure only with a single index. While these are pioneering studies that introduced seismic risks to the evaluation of civil engineering structures, it is 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.

In other words, it is necessary to consider the seismic risks reflecting the damage and collapse process of a structure caused by various seismic forces, in order to consider seismic risks rationally. It is also necessary to find the seismic force for seismic design taking the above factors into account and to calculate design solutions based on it.

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 paper. 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 of public structures.

As an attempt to establish a seismic design method with consideration to seismic risks, this paper presents an approach to determine target seismic design forces by applying the optimum seismic design system developed by the authors. With this system, design solutions including the details of reinforcing bar arrangement of the target structure can also be obtained. The target seismic design values for several structures are then calculated and the results are compared.

This paper consists of the chapters presented below.

2. TARGET SEISMIC DESIGN FORCE

This chapter 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.

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.

2) **Setting of the seismic waveform, hazard curve and range of seismic forces**
   Appropriate seismic waveform$^3, 4)$ and hazard curve$^8, 9, 10)$ are set for the target region. The incremental value $\Delta S$ and division number $N_S$ of the seismic forces are also set as shown in **Fig. 2**.

3) **Setting of the seismic force**
   Based on the range of seismic forces set in 2), the seismic force for optimum seismic design $S_i (i = 1 \sim N_S)$ is set.

4) **Optimum seismic design**
   Optimization of seismic design is performed for each seismic force $S_i (i = 1 \sim N_S)$. 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 $S_i$. The optimum solution is calculated through the optimization of the response surface using the RBF network and Genetic Algorithm$^{17)}$ under the minimized initial construction cost$^{14), 15)}$. The initial construction cost of the optimum design solution obtained is presented as $C^0_i (i = 1 \sim N_S)$.

5) **Calculation of the seismic risk cost**
   The seismic risk cost $C_r^i (i = 1 \sim N_S)$ 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 $N_i$ times for each design solution. The method for calculating the seismic risk cost is as mentioned below.

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 $C^{'}_i (i = 1 \sim N_S)$ is calculated by adding the initial construction cost $C^0_i$ of the design solution found in 4) to the seismic risk cost $C^{'}_i$ found in 5),

$$C^{'}_i = C^0_i + C^{'}_i \quad (i = 1 \sim N_S) \quad (1)$$

7) **Calculation of the target seismic design force**
   The above calculation is performed to calculate the total cost $C^{'}_i$ for each $S_i$. **Fig. 2** is a conceptual diagram of the relationship between the total cost $C^{'}_i$ and seismic force $S_i$. Of these $C^{'}_i$ values, the seismic force corresponding to the minimum total cost $C^{'}_{min}$ is the target seismic design force.

While the optimum solution for each seismic force must be found and relatively complex procedures must be followed in the flow presented in **Fig. 1**, it is possible to develop a fully automatized design system$^{14), 15)}$. It is thus thought not to be a great burden on the designer.
3. SEISMIC RISK COST

As mentioned before, the total cost for each seismic force is calculated by totaling the initial construction and seismic risk costs. The seismic risk cost is usually calculated using damage and hazard curves. In this study, 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 chapter first defines the damage to an RC structure, and then describes the method for calculating seismic risk costs.

(1) Definition of damage
In this study, damage is defined for all elements where nonlinearity is taken into account. The \( M-\theta \) relationship of a tetra-linear model, which is represented by the thick gray line in Fig. 3, is used as the relationship between the nonlinearity of RC elements and damage (Example 2 below), in accordance with the method defined in the Design Code for Railway Structures and instruction manual (seismic design) \(^2\). In addition, the \( M-\theta \) relationship of a tri-linear model represented by the dashed line in Fig. 3 is also used for the skeleton curve as the relationship between the nonlinearity of RC elements and damage (Example 1 below), as provided in the Standard Specifications for Concrete Structures\(^18\). The relationship between this skeleton curve and damage can be handled in the same way as the skeleton curves of railway structures\(^18\). This skeleton curve is a precisely simplified version of the above-mentioned tri-linear skeleton curve, and the relationship between the bending moment and damage is equivalent. In the figure, \( \theta_\mathrm{c} \) is the angle of rotation at the time of cracking, \( \theta_\mathrm{y} \) is the angle of rotation at the time of yield, \( \theta_\mathrm{m} \) is the maximum angle of rotation to maintain \( M_\mathrm{m} \), and \( \theta_\mathrm{n} \) is the maximum angle of rotation to maintain \( M_\mathrm{y} \).

Classified degree of damage is defined as degree 1 if the maximum response angle of rotation found from time history response analysis is \( \theta_\mathrm{y} \) or smaller, degree 2 if it is \( \theta_\mathrm{m} \) or smaller, degree 3 if it is \( \theta_\mathrm{n} \) or smaller and degree 4 if it exceeds \( \theta_\mathrm{n} \)\(^2\).

(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.

Table 1 presents the damage matrix using a single-layer portal rigid-frame structure shown in Fig. 4 as an example. 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 shows the node numbers displayed in Fig. 4 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) Calculation of seismic risk costs
In this study, the seismic risk cost is calculated using a damage matrix representing the relationship between the seismic force and damage as shown in Table 1 and a hazard curve (8, 9, 10) 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, where, $C'_i = \frac{N}{\sum h(S_j) \cdot c_{ij} \cdot \Delta S}$ (i = 1~N)

where, $C'_i$ 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 study, 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 $\Delta S$.

4. EXAMPLE 1 OF THE CALCULATION OF THE TARGET SEISMIC DESIGN FORCE
In this chapter, the target seismic design force of an RC rigid-frame pier is calculated as Example 1. The optimum design problem and calculation results are as presented below.
where, \( g'_{jk} \) 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 \( JN \), diameter of reinforcing bars in the axial direction \( D \), placing of shear reinforcement \( NW \) and spacing of shear reinforcement \( SV \).

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 2 lists the potential values of design variables. By setting the minimum spacing of reinforcement as the diameter of reinforcement \( D \times 2.5 \) (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 24 N/mm² and SD345 reinforcement are used.

(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,

\[
c_y = \sum_{i=1}^{N_c} c^{mw}_{ij} \quad (i = 1 \sim N_c, j = 1 \sim N_s) \tag{8}
\]

where, \( c^{mw}_{ij} \) 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 \( c^{rep}_{ij} \) 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 study, different repair methods are adopted for the lower and upper ends of column members and upper beam sections.

Table 3 presents the damage conditions and repair methods corresponding to the damage of different members\(^{12,13}\). 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\(^{18}\) of an inland-type earthquake with Level 2 earthquake motion is used as the input earthquake motion for time history response analysis and the calculation of the seismic risk cost, and 3 hazard curves\(^{19}\) (0.16, 0.50 and 0.84 in fractile) displayed in Fig. 9 are adopted.

(3) Calculation results

The calculation results for the RC rigid-frame pier are presented. The calculation is performed for seismic forces of 50 to 1,000 gal on the assumption that the dividing width \(\Delta S\) is 50 gal and the dividing number \(N_s\) 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, \(N_F\) and \(N_B\) represent the numbers of reinforcing bars in the column and beam sections, respectively. Fig. 10 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 250 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 250 gal or greater. The initial construction cost sharply increases between 600 and 650 gal. With respect to the design variables of both design solutions in Table 4, a section width of 1,800 mm is necessary when the seismic force is 650 gal, while the seismic performance is satisfied with a

| Degree of damage | Damage condition | Repair method |
|------------------|------------------|---------------|
| 1                | Slight bending cracking | None          |
| 2                | Yield of reinforcement in the axial direction | Scaffolding Grouting of cracks |
| 3                | Flaking of concrete cover in the axial direction | Scaffolding Grouting of cracks |
| 4                | Damage of internal concrete | Temporary support of slab |
|                  | Break of reinforcement in the axial direction | Replacement of reinforcement |
|                  | Break of lateral ties | Concrete placement |

Table 3 Damage conditions and repair methods.

| \(S_i\) (gal) | \(B\) (mm) | \(H\) (mm) | \(N_F\) | \(N_B\) | \(J_F\) | \(D\) (mm) | \(N_w\) | \(S_F\) (mm) | \(OBJ (C_i)\) (unit \(\times 10^3\)) |
|--------------|-----------|-----------|--------|--------|--------|-----------|--------|-------------|------------------|
| 50           | 1000      | 1200      | 9      | 9      | 1      | 22        | 1      | 200         | 11642            |
| 100          | 1000      | 1200      | 9      | 9      | 1      | 22        | 1      | 200         | 11642            |
| 150          | 1000      | 1200      | 9      | 9      | 1      | 22        | 1      | 200         | 11642            |
| 200          | 1000      | 1200      | 9      | 9      | 1      | 22        | 1      | 200         | 11642            |
| 250          | 1000      | 1200      | 9      | 9      | 1      | 22        | 1      | 200         | 11642            |
| 300          | 1000      | 1200      | 10     | 10     | 1      | 22        | 2      | 200         | 12150            |
| 350          | 1000      | 1200      | 10     | 10     | 1      | 25        | 2      | 200         | 12694            |
| 400          | 1000      | 1200      | 13     | 14     | 2      | 22        | 2      | 200         | 14205            |
| 450          | 1000      | 1200      | 18     | 23     | 2      | 22        | 2      | 100         | 16456            |
| 500          | 1000      | 1200      | 23     | 35     | 2      | 22        | 2      | 200         | 22075            |
| 550          | 1000      | 1500      | 25     | 27     | 2      | 22        | 2      | 200         | 25230            |
| 600          | 1000      | 1500      | 16     | 18     | 2      | 32        | 2      | 100         | 27326            |
| 650          | 1000      | 2000      | 23     | 24     | 2      | 32        | 3      | 100         | 47998            |
| 700          | 1000      | 2000      | 24     | 28     | 2      | 32        | 3      | 100         | 53707            |
| 750          | 1000      | 2000      | 36     | 44     | 2      | 25        | 3      | 100         | 58223            |
| 800          | 1000      | 2000      | 31     | 33     | 2      | 25        | 4      | 100         | 64404            |
| 850          | 1000      | 2000      | 22     | 24     | 2      | 32        | 4      | 100         | 65973            |
| 900          | 1000      | 2000      | 36     | 37     | 2      | 25        | 4      | 100         | 66235            |
| 950          | 1000      | 2000      | 37     | 39     | 2      | 25        | 4      | 100         | 71299            |
| 1000         | 1000      | 2500      | 26     | 29     | 2      | 32        | 4      | 100         | 73080            |

Fig. 9 Hazard curves\(^{19}\).

Table 4 Design solution by seismic force \(S_i\).

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Fig. 10  Initial cost and total repair cost by seismic force.

Table 5  Damage matrix.

| Seismic force (gal) | Initial construction cost | Total repair cost |
|--------------------|---------------------------|-------------------|
| 50                 | 1000                      | 2000              |
| 100                | 2000                      | 4000              |
| ...                | ...                       | ...               |
| 1000               | 10000                     | 20000             |

section width of 1,300 at 600 gal. The objective function thus increases sharply between 600 and 650 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 7 sections in the direction of the bridge axis and 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, 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.

Damage is studied for design solutions at 250 gal or more, where the initial construction cost is the minimum. In the case of design solutions with seismic forces of 250 to 400 gal, collapse occurs with a seismic force 50 gal stronger than the seismic force used for design. In the case of design solutions with seismic forces of 450 to 600 gal, however, collapse does not occur even when the input seismic force is 50 to 150 gal stronger than the seismic force used for design. For design solutions at 650 gal or more, where the objective function increases sharply in Fig. 10, collapse does not occur even with a seismic force of 1,000 gal.

Next, the symbol ◆ in Fig. 10 represents the total repair cost for each design solution calculated from the damage matrix in Table 5. The total repair cost is found by totaling 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 total repair cost at 650 gal or more, where the initial construction cost increased sharply, is around one-fourth or one-fifth of the repair cost in case of seismic forces smaller than 650 gal. This is, as can be seen from Table 5, because collapse would not occur in design solutions at 650 gal or more even with the input of the maximum assumed seismic force of 1,000 gal.

Figs. 11 to 13 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. 9 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.
The target seismic design force is 300, 400 and 450 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.

5. EXAMPLE 2 OF THE CALCULATION OF THE TARGET SEISMIC DESIGN FORCE

This section presents the calculation results for an RC rigid-frame viaduct as Example 2 of the calculation of the target seismic design force. The optimum design problem and examples of numerical calculation will be presented below.

(1) Optimum design problem

The subject of Example 2 is a standard single-layer RC rigid-frame railway viaduct with a spread foundation shown in Fig. 14. The figure illustrates the direction perpendicular to the bridge axis on the left and the direction of the bridge axis on the right. Nonlinearity is taken into account for the column and beam members. The M-θ relationship of a tetra-linear model displayed in Fig. 3 is used for members for which nonlinearity is taken into account.

The direct construction cost is used as the objective function, and is calculated in the same way as equation (3). Constraints are conditions concerning the angle of rotation and shear force, and are calculated in the same way as equations (6) and (7). While there are 7 design variables in the same way as in the previous chapter, potential values are different. Table 6 lists the potential values of design variables. While the number of reinforcing bars in the axial direction is calculated in the same way as in the previous chapter, the maximum spacing of reinforcement is 125 mm. As materials, concrete with a design standard strength of 24 N/mm² and SD345 reinforcement are used. The optimum seismic design and the earthquake motion, seismic loss cost and hazard curve used for the calculation of seismic risks are also the same as those in the previous chapter.

(2) Calculation results

Similarly to Example 1, the calculation is performed for seismic forces of 50 to 1,000 gal on the assumption that the incremental value ΔS is 50 gal and the dividing number Ns is 20 for the seismic forces.

Table 7 and Fig. 15 presents the design solutions for various seismic forces and the changes in initial construction cost for different design solutions, respectively. 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, similarly to the case in the previous chapter. The initial construction cost also increases sharply when the seismic force is between 750 and 800 gal. As shown in Table 7, 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 8 presents the damage matrix of design solutions found for various seismic forces (Table 7). 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. Since it is difficult to display the damage of all sections, the maximum values for columns and beams in the direction of the bridge axis and the direction perpendicular to the bridge axis are presented for each design solution.

In the table, \( P, B, P, \) and \( B \) indicate the maximum damage of the column member in the direction of the bridge axis, the beam member in the direction of the bridge axis, the column member in the direction perpendicular to the bridge axis and the beam member in the direction perpendicular to the bridge axis, respectively.

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.

In Fig. 15, the total repair cost for each design solution is indicated by the symbol ◆ in the same way as in the previous chapter. Compared with the initial construction cost in the figure, the total repair cost tends to decrease with increasing initial construction cost, similarly to the case in the previous section. The difference in total repair cost is small although the initial construction cost of the design solution at

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### Table 6 Potential values of design variables.

| \( B \) (mm) | \( 500\sim1200 \) (100mm intervals) |
| \( H \) (mm) | \( B + 200\sim800 \) (100mm intervals) |
| \( N \) | 8 types depending on \( B \) and \( H \) |
| \( J_\gamma \) | 1 or 2 |
| \( D \) (mm) | 19 or 25 or 29 or 32 |
| \( N_\gamma \) | 1 \sim 4 |
| \( S_\gamma \) (mm) | 100 or 200 |

### Table 7 Design solution by seismic force \((S_i)\).  

| \( S_i \) (gal) | \( B \) (mm) | \( H \) (mm) | \( N_\gamma \) | \( N_\gamma \) | \( J_\gamma \) | \( D \) (mm) | \( N_\gamma \) | \( S_\gamma \) (mm) | \( OBJ \) \( (C^\gamma_o) \) (unit \( \times 10^3 \)) |
|---------------|------------|------------|------------|------------|------------|------------|------------|------------|-----------------|
| 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 |

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**Fig. 14** Structural model (Example 2).

**Fig. 15** Initial construction cost and total repair cost by seismic force.
Table 8 Damage matrix.

![Damage matrix](image)

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.

Next, the seismic risk cost is calculated and the relationship between the total cost and seismic force is found as shown in Figs. 16 to 18. The notation method used for the figures is the same as that in the previous chapter, indicating the results for 0.16, 0.50 and 0.84 fractile hazard curves. 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 the target seismic design
force also varied with differences in the occurrence probability of earthquakes similarly to the case in the previous section. 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.

The target seismic design force in the calculation results of Example 1 is 300, 400 and 450 for 0.16, 0.50 and 0.84 fractile hazard curves, respectively, and is different from the results of Example 2. This means that the target seismic design force varies not only with the occurrence probability of earthquakes, but also with differences in target structures.

The annual probability of exceedence is found using these target seismic design forces calculated in Examples 1 and 2, and based on corresponding hazard curves. In all cases, the annual probability of excess probability is approximately $10^{-3}$. This is partly because only the repair cost for physical damage is included in the seismic risk cost in the above calculation examples. The ratio of the seismic risk cost taking only the repair cost into account to the total cost is lower than that of the initial construction cost. It is presumed that the annual probability of excess is on a similar level for the seismic risk costs of seismic forces with an especially low occurrence probability of earthquakes because their influence on the total cost is low. The fact that the target seismic design forces calculated in this example are all lower than the current seismic design standard may also be because of the same reason. Since the above calculation examples are merely for the confirmation of the variety in proposed target seismic design forces due to differences in the occurrence probability of earthquakes and target structures, only the repair cost that is not affected by the regional characteristics of construction is adopted as the seismic risk cost. Based on these results, calculation taking indirect risks into account will be made in the next chapter.

6. AN EXAMPLE OF NUMERICAL CALCULATION TAKING THE USER COST INTO ACCOUNT

Only the risks associated with physical damage to structures are taken into account in the above-mentioned calculation results. While what should be taken into account concerning seismic risks varies with the country or municipality where structures are constructed, there may be cases where risks affecting the users of such structures are taken into account in addition to risks caused by physical damage. Two of the authors have conducted research on the user cost (UC) as a concept concerning the standard of values of bridges¹⁶). This chapter thus presents the calculation results in the cases where the UC incurred by the users of structures is included in seismic risks.

(1) UC and seismic risk cost

UC is calculated by multiplying the time loss for detouring during the closure of a bridge by the time value. In a study of the time value by car type²⁰), UC ($10^3$ yen/day) is approximately 80 in relatively low areas, 500 on average and 6,000 in relatively high areas. This chapter thus presents the results of the calculation of seismic risks taking the above three types of UC into account, on the assumption that the RC rigid-frame pier presented in 4. is a structure on a road network.

Similarly to the repair cost, UC is related to the damage matrix. In this study, the maximum values of damage to columns and beam members by various seismic forces are found and UC is calculated based on the repair associated with those maximum values or the number of days required for reconstruction following collapse. Table 9 lists the maximum damage, number of days of road closure and UC. The number of days of closure is assumed to be 15, 30, 80 and 100 for degrees of damage of 2, 3, 4 and collapse, respectively. The seismic loss cost $c_{ij}$ in equation (8) is replaced by the equation below in the case of seismic risks taking UC into account,

$$c_{ij} = \sum_{j=1}^{N_x} c_{ij}^{rep} + c_{ij}^{U} (i = 1, 2, 3, 4, \text{ and } j = 1, 2, 3, 4) \quad (9)$$

where, $c_{ij}^{U}$ is the user cost of the structure incurred by the $j$-th seismic force in the design solution de-

| Degree of damage | Number of days of road closure | UC ($\times 10^3$ unit/day) |
|------------------|-------------------------------|-----------------------------|
|                  | Low                           | Medium                      | High                        |
| 1                | 80                            | 500                         | 6000                        |
| 2                | 15                            | 750                         | 90000                       |
| 3                | 30                            | 1500                        | 180000                      |
| 4                | 80                            | 40000                       | 480000                      |
| Collapse         | 100                           | 50000                       | 600000                      |

Table 9 Number of days of road closure and UC to the degree of damage.
signed for the $i$-th seismic force.

(2) Calculation result

This section presents the results of the calculation of the seismic risks where UC is taken into account. Figs. 19 to 21 show the calculation results for the 0.16 fractile hazard curve by UC. The figures display the results in order of relatively low (80), medium (500) and relatively high (6,000) UC. The white, blue and yellow parts in the figures indicate the initial construction cost, seismic risk cost associated with the repair cost and the seismic risk cost associated with UC, respectively. The dashed lines represent the changes in target seismic design force based on the calculation results of 4. (Figs. 11 to 13) where UC is not taken into account.

The target seismic design force is 400 gal when UC is low or medium, and is 600 gal when UC is high. Compared with the value of 300 gal found for the 0.16 fractile hazard curve in the calculation results of 4, where UC is not taken into account, the target seismic design forces are higher regardless of the scale of UC.

Figs. 22 to 24 show the results by UC for the 0.50 fractile hazard curve. The target seismic design force is 450, 600 and 950 gal when UC is low, medium and high, respectively. Compared with the target seismic design force of 400 gal in the case where UC is not taken into account, it can be seen that the target force is higher regardless of the value of UC similarly to the results for the 0.16 fractile hazard curve.

Figs. 25 to 27 present the results by UC for the 0.84 fractile hazard curve. The target seismic design force is 450, 600 and 950 gal when UC is low, medium and high, respectively. While the target seismic design force is 450 gal when UC is low and the same as in the case where UC is not taken into account, it can be seen that the target force became higher when UC is medium or high. In Figs. 20 and 22, the total cost locally became lower at 600 gal. Comparing the design solutions at 600 and 500 gal, the difference in initial construction cost is small, and there is 100 gal difference in seismic force before the occurrence of collapse from that of the damage matrix shown in 4. The degree of influence of the initial construction cost on the total cost is also high when the occurrence probability of earthquakes is low or when UC is relatively low. This result thus indicates that there are seismic forces with small risk even though there is no significant difference in initial construction cost.

Table 10 shows the target seismic design force calculated based on each fractile hazard curve and UC. For comparison, the table also shows the target seismic design force in the case where UC is not taken into account. The values marked with [ ] are the differences in target seismic design values between the cases where UC is and is not taken into account.

Regarding the changes in the target seismic design force by UC, the increase is 0 to 100 gal when UC is relatively low. When UC is on the medium level, the increase is 100 to 200 gal and is greater than when UC is low. When UC is relatively high, the increase is 300 to 550 gal and even greater. These calculation results indicate that the increase in the target seismic design force became more significant when UC is higher and the influence of UC on the calculation is greater. Similarly to the calculation results in the previous chapters, the annual
probability of excess corresponding to the target seismic design force is calculated based on the hazard curve and is found to vary from $10^{-3}$ to less than $10^{-4}$. This is thought to indicate that this method can be used for rational design taking regional and other characteristics into account.

From the above results, it can be seen that UC is an important evaluation value for structures since it has considerable influence on the target seismic design force when it is included in seismic risks. This also suggests the importance of factors that should be included in risks in the risk management of public structures.

**Table 10** Seismic design force (gal) by hazard curve and UC.

| UC  | Hazard curve |
|-----|--------------|
| 0.16| 0.5          |
| None| 300          |
| Low | 400          |
|     | [+100]       |
|     | [+50]        |
|     | [0]          |
| Medium| 400      |
|      | [+100]      |
|      | [+200]      |
|      | [+150]      |
| High | 600         |
|      | [+300]      |
|      | [+550]      |
|      | [+500]      |
7. AFTERWORD

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, the lack of emphasis on the changes in performance or risk, effective repair / reinforcement methods and other factors is pointed out as a problem of the two-level seismic design system\(^5\), \(^6\), \(^7\). Against such a background, this study 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 study 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, as well as the user cost.
- To find the initial construction cost, an optimum design system proposed by the authors based on cost minimization is applied.
- 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.
- Design solutions including details of the reinforcement of the target structure with the minimum total cost can be obtained.

(2) The proposed method for calculating target seismic design forces is applied to two examples. As a result of calculation using three hazard curves with different fractile values, the following knowledge is obtained:

- In those examples, the target seismic design forces vary with difference in the occurrence probability of earthquakes. When the probability is higher, the target force also become higher. The range of 300 to 450 gal and 400 to 550 gal is used for Examples 1 and 2, respectively.
- The target seismic design force differs between Examples 1 and 2 even in calculation using the same occurrence probability of earthquakes. Since the seismic waveform and hazard curve used for analysis are the same for both examples, it means that the target seismic design forces varies with difference in target structures. The range of forces is between 50 and 100 gal in these examples.

(3) Seismic risk costs in (2) are found by considering the costs for the repair of physical damage or for the reconstruction of structures. The loss incurred by users of a bridge is thus taken into account, and analysis is performed by including UC in seismic risk costs. As a result, the target seismic design forces tend to increase when UC is higher and the importance of the risk of users is indicated.

(4) It is found that the seismic design force with minimum total cost varied with the occurrence probability of earthquakes and structural types. With the current seismic design methods based on Level 1 and 2 seismic forces, it is difficult to directly consider the influence of these factors. It is thus indicated that seismic design forces taking seismic risks into account must be set separately.

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. While the proposed method requires the calculation of structural optimization and other complicated procedures, the burden on the designer is thought to be small because everything is systematized. In recent years, the occurrence probability of earthquakes is becoming more common as it is presented in the form of a probabilistic seismic hazard map at the Seismic Hazard Information Station of the National Research Institute for Earth Science and Disaster Prevention\(^{21}\). 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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(Received February 22, 2008)