INTERACTION OF NONLINEAR RESPONSE BETWEEN PIER AND ISOLATOR IN SEISMICALLY ISOLATED BRIDGES

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SUMMARY

This paper deals with the nonlinear interaction between pier and isolator in seismically isolated bridges subjected to extreme earthquakes. Isolated bridges with RC pier and Lead Rubber Bearing (LRB) are modeled as a 2DOF system. In particular, the investigation focused on the effect of the primary structural parameters such as yield strength ratio on the displacement ductilities of both pier and isolator. Further, to identify the range of yielding strength ratio as all the restrictions on some typical nonlinear responses of isolated bridges under severe earthquakes are satisfied, a practical procedure using the contour diagrams for those responses is introduced.

INTRODUCTION

A lot of seismic isolation systems have been developed in many countries since the early 1970s because of their effectiveness in reducing earthquake design force. This force reduction is basically based on increasing both the period of vibration and the energy dissipation capacity of a structure. In Japan also, especially since 1995 Kobe earthquake, the seismic isolation design has been extensively adopted for new road bridge construction and many existing road bridges has been seismically retrofitted by installing seismic isolation devices. Though it is desirable that the responses of the piers of seismically isolated bridges are linear during a design earthquake, there is every possibility that the piers behave nonlinearly during an extreme earthquake as well as the seismic isolation devices. In this study, a wide variety of parametric analyses have been carried out in order to elucidate the nonlinear interaction between the isolation device and the pier. To this end, an example of the procedure to identify the effective ranges of some main structural parameters by overlapping contour diagrams as satisfy the restrictions on some important nonlinear responses of seismically isolated bridges under strong earthquakes is introduced.

ANALYTICAL METHOD

Seismically isolated bridges in which the lead-rubber bearings (LRB) are installed between the superstructures and the RC piers are modeled as a two-mass shear system with rigid foundation. A non-dimensionalized form of equations of motion for this system is developed help identify structural and isolator parameters which influence system response.

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Structural Idealization

Figure 1 shows the seismically isolated bridge that is modeled as a two-degree of freedom (2DOF) system with the rigid foundation and its deformations. In **Figure 1**, m_1 and m_2 are the masses of pier and superstructure respectively, c_1 and c_2 are the damping coefficients of pier and isolation device respectively, k_{01} and k_{02} are the initial stiffnesses of pier and isolation device respectively, x_1 and x_2 are the structural displacements of pier and isolation device respectively, y_2 is the relative displacement of superstructure to the foundation, and x_G is the ground displacement. Non-isolated bridges can be represented as 2DOF systems with infinitely large values of the initial stiffness and the yield strength of isolation device.

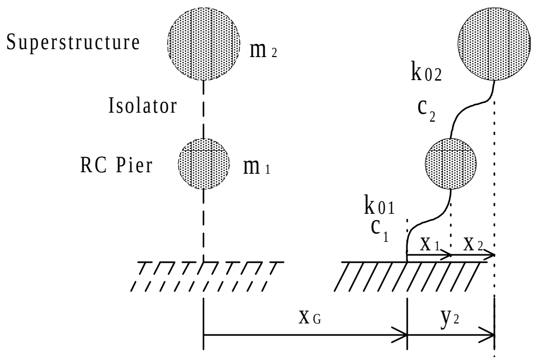


Figure 1: 2DOF model of seismically isolated bridge

The hysteresis models of the pier and the isolator follow the Q-hyst and Bilinear models shown in **Figures 2** and **3**, respectively [Saiidi, 1982]. In these figures, Q_1 and Q_2 are the restoring forces of pier and isolation device respectively, Q_{y1} and x_{y1} are the yield restoring force and displacement of pier respectively, Q_{y2} and x_{y2} are the yield restoring force and displacement of isolation device respectively, and γ_1 and γ_2 are the ratios of the post yield stiffness to the initial stiffness of these models respectively.

Equation of Motion

Assuming that the restoring force-displacement relationships of both piers and isolators are linear within a short time, the equation of motion of two-mass shear systems like that shown in **Figure 1** can be written as

$$[m]\{\ddot{y}\} + [c]\{\dot{y}\} + [k]\{y\} + \{u\} = -[m]\{1\}\ddot{x}_G \tag{1}$$

where *[m]*, *[c]* and *[k]* represent the mass, damping and stiffness matrices respectively, $\{\ddot{y}\}$, $\{\dot{y}\}$ and $\{y\}$ are the acceleration, velocity and displacement vectors respectively, and $\{u\}$ is the load vectors.

Equation (1) represents the equation of motion for the relative displacements of the masses to the foundation. By using a transform matrix *[D]*, **Equation (1)** can be transformed to **Equation (2)** which is the equation of motion for the relative displacements (x_1, x_2) of both stories [Nariyuki, etc., 1997].

$$[D][m][D]^T\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} + \{u\} = -[D][m]\{1\}\ddot{x}_G \tag{2}$$

where $\{\ddot{x}\}$, $\{\dot{x}\}$ and $\{x\}$ are the relative acceleration, velocity and displacement vectors respectively, and *[C]* and *[K]* represent the diagonal damping and stiffness matrices. For convenience to use in MDOF time

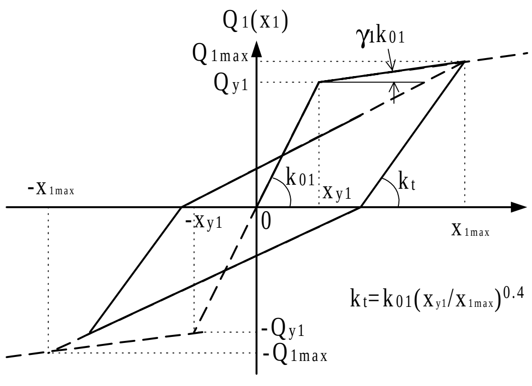


Figure 2: Q-hyst model of force-displacement relationship of piers

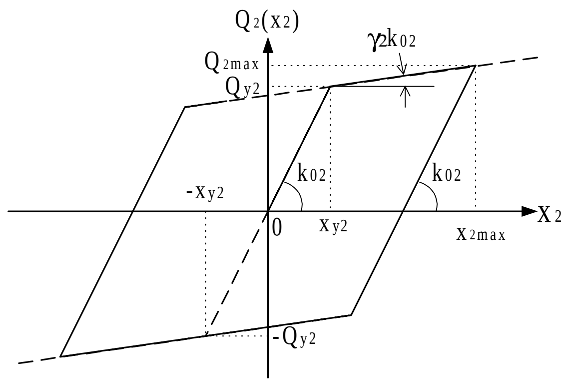


Figure 3: Bilinear model of force-displacement relationship of isolators

integration analyses, the damping matrix $[C]$ is assumed to be proportional to the initial stiffness matrix $[K_0]$.
In order to help generalize the results of any analysis performed on this idealized system, **Equation (2)** will be normalized in terms of the product of the mass, m_1, and yield displacement, x_{y1}, of pier [Nariyuki, etc., 1997]. The normalized equation of motion for the 2DOF system can then be written as

$$\eta^2\rho^2[\alpha][D]^T[\xi]\{\ddot{x}\} + 2h\eta\eta_0\omega_p[D]^{-1}[\beta][\xi]\{\dot{x}\}$$
$$+\omega_p^2[D]^{-1}[\beta][\nu][\xi]\{x\} + \omega_p^2[D][\beta][\xi]\{\upsilon\} = -\omega_p^2 R_I \frac{[\alpha]}{\sum_{i=1}^{2}\alpha_i}\{1\}\ddot{z}_G \quad (3)$$

where $[\alpha]$ and $[\beta]$ are the normalized diagonal mass and stiffness matrices which have the mass and stiffness ratios, $\alpha=m_2/m_1$ and $\beta=k_{02}/k_{01}$, respectively as a element. In **Equation (3)**, $[\nu]$ is the elasto-plastic stiffness matrix whose elements are the ratios of the stiffness at time t to initial stiffness of each story, $\{\upsilon\}$ is the vector whose elements are $\upsilon_i=u_i/Q_{yi}$,(i=1,2), h is damping factor of the first mode, η is the ratio of the predominant circular frequency of input waves, ω_p, to the first-mode natural circular frequency, ${}_1\omega_0$, ρ is the ratio of ${}_1\omega_0$ to the natural circular frequency, ω_{01}, of piers, η_0 is the ratio of the first-mode natural period of an isolated bridge to that of a non-isolated bridge with same pier and superstructure. And also $\{x\}$ represents the relative displacement vector whose elements are the relative displacements, x_1 and x_2, divided by the yield displacements, x_{y1} and x_{y2}, of each story respectively, and $\{\ddot{x}\}$ and $\{\dot{x}\}$ are the relative acceleration and velocity vectors respectively, $[\xi]$is the matrix whose elements are yield strength ratio $\xi_i=x_{yi}/x_{y1}$ (i=1,2). Further, in **Equation (3)**, $\ddot{z}_G$ is the acceleration normalized in terms of the peak ground acceleration $\ddot{x}_{G\,max}$, and R_I is the input intensity ratio, which represents the ratio of the inertial force of bridges assumed to be rigid to the yield restoring force, Q_{y1}, of piers as

$$R_I = \sum_{i=1}^{2} m_i \ddot{x}_{G\,max} \Big/ Q_{y1} \quad (4)$$

From **Equation (3)**, it can be seen that the seismic responses of structures like that shown in **Figure 1** are governed by the nine structural parameters as

1) T_p : Predominant period of input ground motions
2) R_I : Input intensity ratio
3) h : Damping factor in the first mode
4) T_0 : Elastic natural period of non-isolated bridges
5) ${}_1T_0$: Elastic first-mode natural period of isolated bridges
6) α : Mass ratio (m_2/m_1)
7) ξ : Yield displacement ratio (x_{y2}/x_{y1})
8) γ_i : Elasto-plastic stiffness ratio (i=1,2)
9) $\overline{Q}$: Yield strength ratio ($Q_{y2}/Q_{y1}=\beta\xi$)

Equation (3) can be solved numerically for the normalized relative displacements, $\{x\}$, given an earthquake record ($\ddot{x}_G(t)$) and the structural parameters mentioned above.

Equilibrium equation of energy response

The equation of motion (**Equation (2)**) for an isolated bridge excited by a ground acceleration can be rewritten in energy form by multiplying each term by the relative velocity vector $\{x\}$ and integrating over time as

$$\sum_{i=1}^{2}\frac{1}{2}m_i\dot{y}_i^2 + \sum_{i=1}^{2}\int_0^t c_i\dot{x}_i^2 dt + \sum_{i=1}^{2}\int_0^t Q_i(x_i)\dot{x}_i dt = \sum_{i=1}^{2}\int_0^t(-m_i\dot{y}_i\ddot{x}_G)dt \quad (5)$$

where the terms on the left-hand side in this equation can be regarded as kinetic, damping and strain energy, W_{Ki}, W_{Di} and W_{Hi} (i=1,2), respectively and the term on the right-hand side represents input energy, E_i (i=1,2). The strain energy of each story is the sum of elastic and hysteretic energies. At the end of seismic response, the kinetic and elastic energies vanish and W_{Hi} (i=1,2) represent the hysteretic energies which are strongly related to seismic damages to isolated bridges.

Damage index

In this study, displacement ductilities (μ_{Di}, i=1,2) defined as **Equation (6)** are utilized to evaluate the seismic damage to piers (i=1) and isolators (i=2).

$$\mu_{Di} = \frac{|x_i|_{max}}{x_{yi}} \qquad (i=1,2) \tag{6}$$

where $|x_i|_{max}$ and x_{yi} are the maximum and yield displacements respectively of i-th story as shown in **Figures 2** and **3**.

PARAMETRIC INVESTIGATION ON NONLINEAR INTERACTION BETWEEN PIER AND ISOLATOR

The nonlinear response analyses of isolated bridges with the values of parameters listed in **Table 1** were carried out. Though the practical range of yield strength ratio $\overline{Q}$ may be between 0.1 and 1.0 at the widest estimate, in order to grasp the trend of the effect of $\overline{Q}$ on the damages to piers and isolators. The intensity of input accelerations is represented in terms of input intensity ratio R_I as mentioned above. In seismic response analyses, the values of R_I are adjusted as the displacement ductilities μ_D of non-isolated bridges with the same pier and superstructure as those of isolated bridges are equal to the required values for instance, μ_D=6.0 as shown in **Table 1**. The non-isolated bridges are represented by assuming that both stiffness and yield force of isolators are approximately infinity. In this study, three different ground motion records, i.e. Kobe, Hachinohe and El Centro records, were utilized as input waves.

Table 1: Fixed value of each parameter in Figures 4-7

Parameters	Fixed values
Damage to non-isolated bridge ƒ Ê D	6.0
Mass ratio ƒ ¿	2.0
Elasto-plastic stiffness ratio ƒ Á 2	0.15
Yield displacement ratio ƒ Ì	0.5
Yield strength ratio $\overline{Q}$	0.01 Ì10.0
Natural period of non-isolated bridge $T_{0\ (sec)}$	0.60
Damping factor h	0.05

Effects of Yield Strength and Displacement Ratios on Damages to Pier and Isolator

Figure 4(top) shows $\overline{Q}$ -μ_{D1}-ξ relationships and **Figure 4**(bottom) shows $\overline{Q}$ -μ_{D2}-ξ relationships for Kobe record. It can be seen that, regardless of the values of ξ, μ_{D1} is approximately equal to μ_D(=6.0) for $\overline{Q}$ greater than 1.0 and about 1.4 for the $\overline{Q}$ less than 0.1. The isolated bridges in the former may be equivalent to non-isolated bridges and those in the latter may be equivalent to only pier structures. It is also apparent that the damages to piers and isolators tend to increase with decreasing the yield displacement ratio ξ under the condition that $\overline{Q}$ is constant and $\overline{Q}$ -μ_{D1} curves plotted for ξ greater than 0.3 agree with each other as the same as $\overline{Q}$ -μ_{D2} curves. It may be possible to identify the primary parameters such as yield strength ratio considering the balance between the damages to pier and isolator.

Effects of Natural Period of Non-isolated Bridges on Interaction of Nonlinear Response

Figure 5 shows the effects of natural period T_0 of non-isolated bridges on μ_{D1} and μ_{D2}. It can be seen that the $\overline{Q}$ -μ_{D1} curves plotted for T_0 longer than 0.4 (sec.) agree within the range of $\overline{Q}$ greater than about 0.5 and the values of μ_{D1} for T_0 shorter than 0.4 (sec.) exceed μ_D(=6.0), while all $\overline{Q}$ -μ_{D2} curves are almost identical to each other in the range of $\overline{Q}$ greater than 0.5.

Effects of Damage to Non-isolated Bridges on Interaction of Nonlinear Response

As shown in **Figure 6**, if the value of μ_D is less than 6.0, μ_{D1} is larger than the corresponding μ_D in a range of $\overline{Q}$, i.e., the ranges of $\overline{Q}$ greater than 0.55 and 0.75 for μ_D=2.0 and 4.0 respectively. This may suggest that it is relatively difficult to determine the effective range of $\overline{Q}$ for isolated bridge with relatively smaller μ_D . It is also

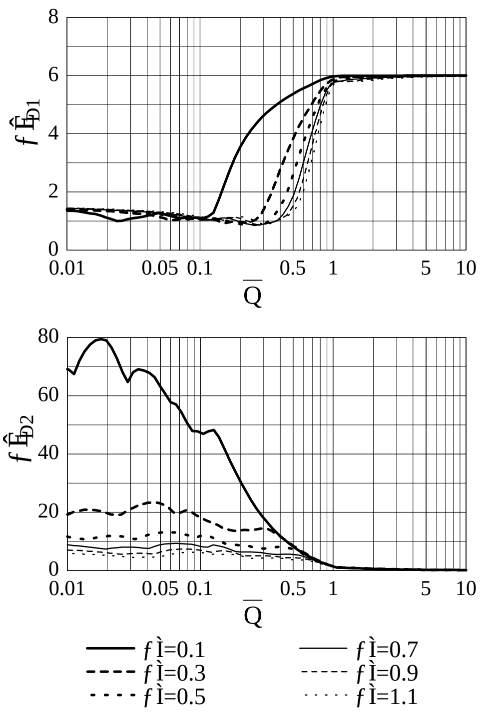


Figure 4: Effects of yield strength ratio on damages to pier and isolator

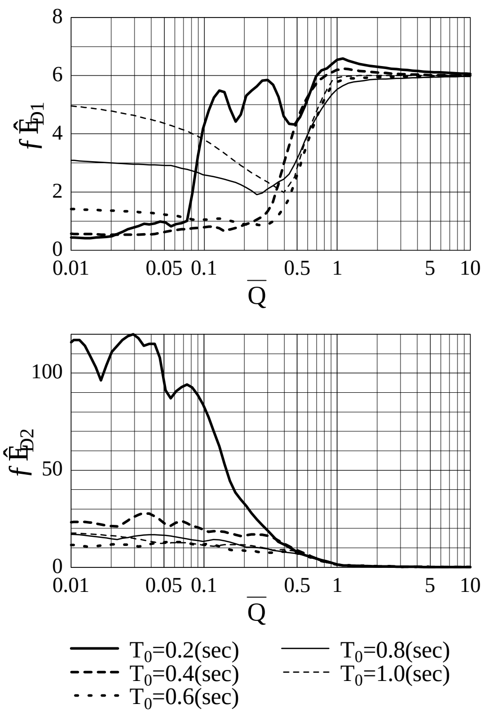


Figure 5: Effects of natural period of non-isolated bridge on damages to pier and isolator

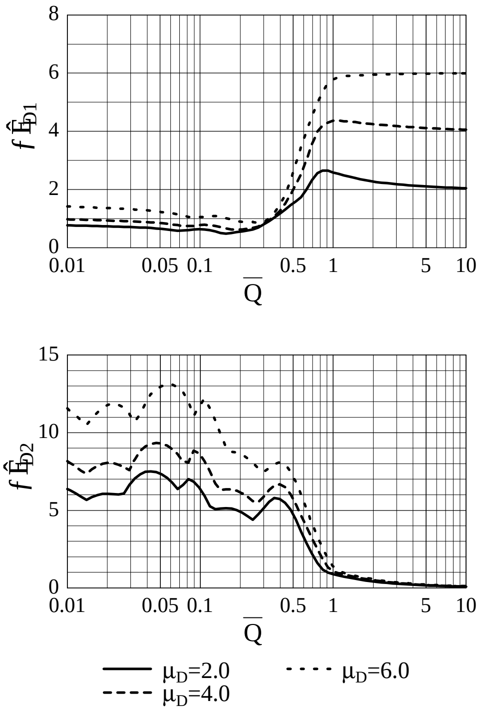


Figure 6: Effect of the damage level of non-isolated bridge on damages to pier and isolator

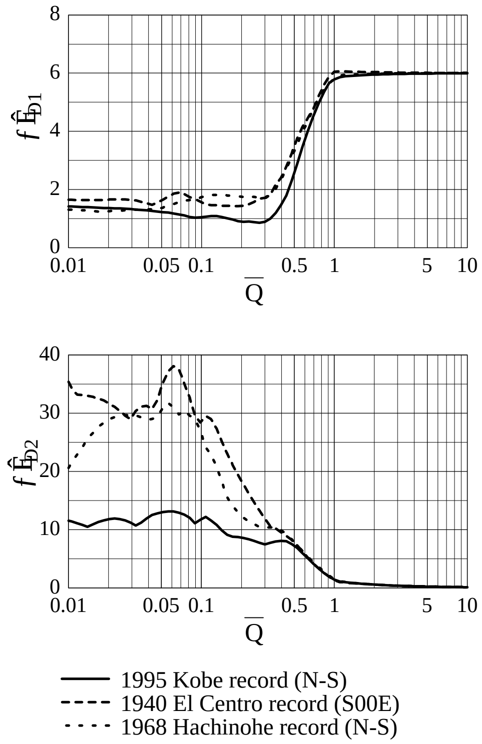


Figure 7: Effects of the difference of input ground motions on damages to pier and isolator

seen in **Figure 6** that $\overline{Q}$ -μ_{D1} curves almost come in contact with each other at $\overline{Q}$ of about 0.4 and μ_{D2} correspond to this $\overline{Q}$ represents one of the maximum value regardless of μ_D . Further, within the range of $\overline{Q}$ between this value and a value as μ_{D1} almost reaches to the corresponding μ_D, μ_{D1} and μ_{D2} tend to increase and decrease linearly with increasing $\overline{Q}$ respectively.

Effects of Deference of Input Waves on Interaction of Nonlinear Response

As seen in **Figure 7**, the curves plotted for El Centro and Hachinohe records are very close and the curve for Kobe record gives smaller values in both top and bottom figures. This means that isolators such as LRB are more effective in protecting isolated bridges subjected to impactive earthquake ground motions with relatively shorter predominant period such as Kobe record.

IDENTIFICATION OF ALLOWABLE RANGES OF PARAMETERS USING CONTOUR DIAGRAMS

In general, it is difficult to determine the characteristics of isolation devices due to a number of restrictions on responses of isolated bridges subjected to strong earthquake motions. A method for identifying the effective range of the main structural parameters of isolated bridges using contour diagrams is presented here [Megawati, 1998].

Hypothetical Restrictions on Some Structural and Response Parameters

It can be desirable that the primary responses of isolated bridges under severe earthquake ground motions will be less than the corresponding least upper bounds respectively. In this study, we hypothetically imposed the restrictions on one structural and four response parameters as follows:

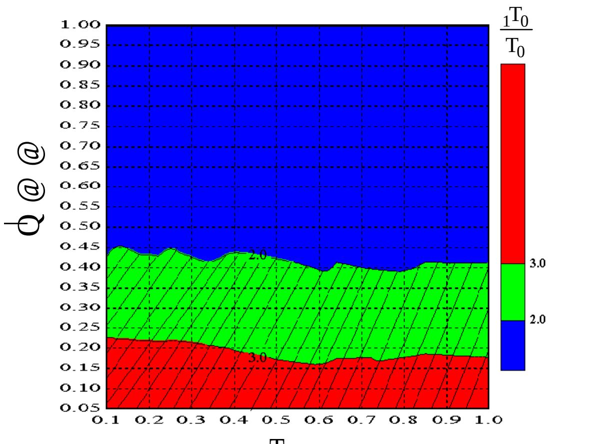
1)The ratio of the elastic first-mode period of isolated bridges to the elastic period of non-isolated bridges ${}_1T_0/T_0$□2.0
(In the Japanese design manual for base-isolated highway bridges, it is stipulated that this ratio is greater than about 2.0.)
2)The displacement ductility of piers μ_{D1}□1.0
(This means that there are no seismic damages to piers.)
3)The displacement ductility of isolators μ_{D2}□8.0
4)The ratio of the hysteretic energy of isolator to that of isolated bridge $W_{H2}/(W_{H1}+W_{H2})\times100$□90%
5)The ratio of the residual displacement u_{BR} to the design displacement u_B $u_{BR}/u_B\times100$□10%
(In the Japanese design manual for base-isolated highway bridges, it is stipulated that this ratio is less than about 10% [Ministry of Construction, 1998]. In this study, it is assumed that u_B is equal to $|x_2|_{max}$.)

Contour Diagrams for Parameters with Restriction

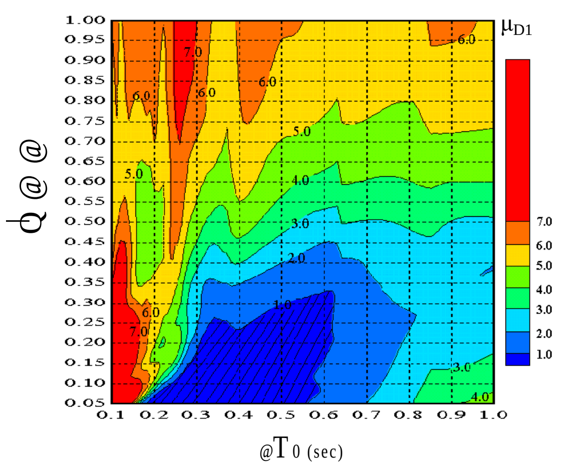
The energy response analyses of isolated bridges with the structural parameter values listed in **Table 2** were carried out for Kobe record (NS, 1995). Based on the analytical results, the relations between yield strength ratio $\overline{Q}$ and natural period T_0 of non-isolated bridges for each parameter mentioned above are shown in **Figures 8 a)-e)** respectively. These figures were drawn through the graphic software WSCNT developed for contours. In these figures, the areas covered with slanted lines indicate the allowable combinations of $\overline{Q}$ and T_0 for the restriction on each parameter. It appears from these figures that the contour lines except for ${}_1T_0/T_0$ are relatively complicated.

Table 2: Fixed value of each parameter in Figures 8 a)-e)

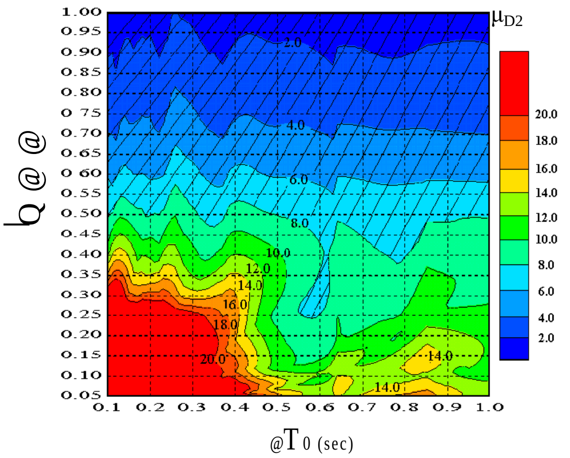
Parameters	values
Damage to non-isolated bridge ƒ Ê$_D$	6.0
Mass ratio ƒ ¿	2.0
Elasto-plastic stiffness ratio ƒ Á$_2$	0.15
Yield displacement ratio ƒ Ì	0.5
Yield strength ratio $\overline{Q}$	0.05 Ì1.00
Natural period of non-isolated bridge $T_{0\,(sec)}$	0.1 Ì1.0
Damping factor h	0.05



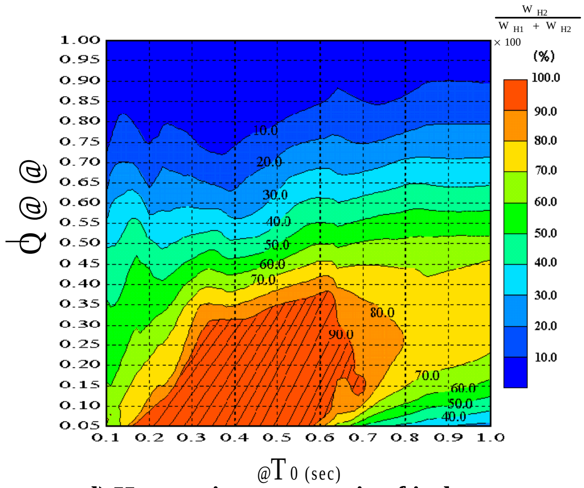
a) Natural period ratio



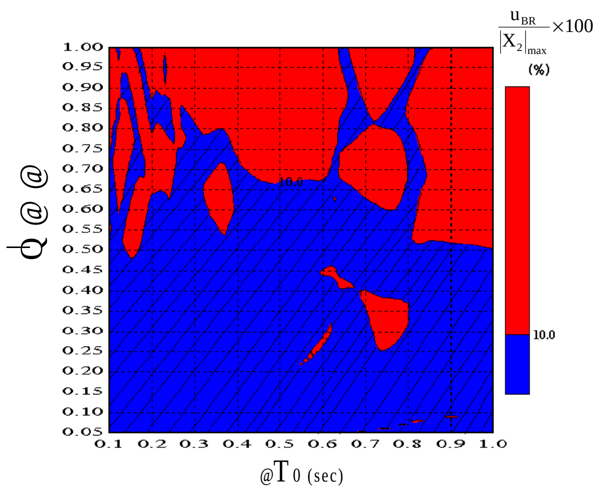
b) Damage to pier



c) Damage to isolator



d) Hysteretic energy ratio of isolator



e) Residual displacement of isolator

Allowable region of (T_0 , $\bar{Q}$) for each parameter

Restriction on each parameter

a) ${}_1T_0 / T_0$ □2.0

b) μ_{D1} □1.0

Figure 8: Contour diagrams for parameters with hypothetical restriction

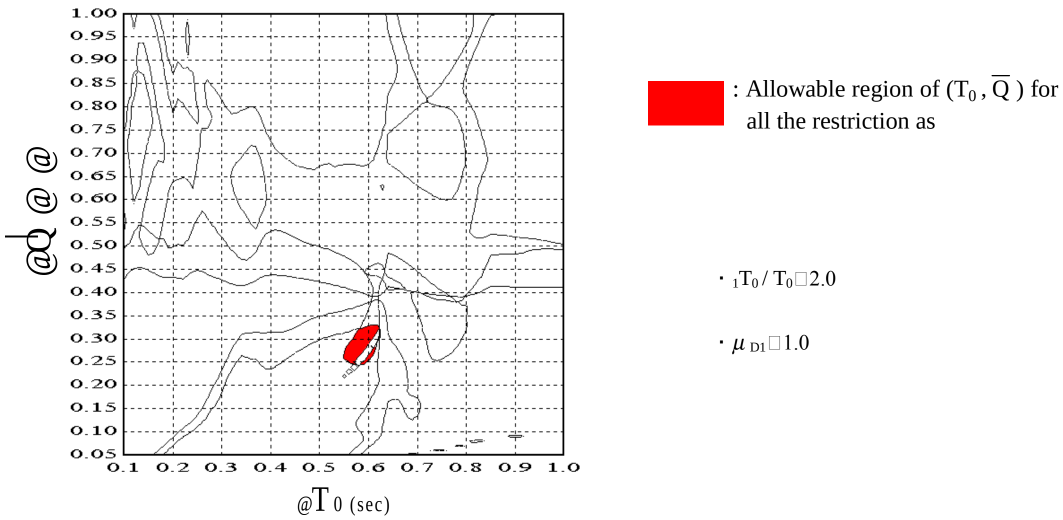


Figure 9: An example of allowable region of $(T_0, \overline{Q})$

An Example of Allowable Region of $(T_0, \overline{Q})$ obtained by overlapping Contour Diagrams

In order to obtained the allowable region of (T_0, $\overline{Q}$) which satisfy all the above-mentioned requirements, **Figures 8 a)-e)** were overlapped on a personal computer. **Figure 9** shows the allowable region of (T_0, $\overline{Q}$) under all the restrictions assumed here. It can be seen that in this case the allowable area is relatively narrow and almost determined from the restrictions of μ_{D1} and μ_{D2}. If there is no allowable regions, the restrictions on some parameters should be reasonably relaxed

CONCLUSIONS

The displacement ductilities of pier and isolator of isolated bridge increase and decrease respectively with increasing the yield strength ratio in broad perspective. It may be possible to design the isolated bridges as the arbitrary damages to both pier and isolator are allowed for extreme earthquakes. The larger the displacement ductility of non-isolated bridge piers, the more effective the isolators are in reducing the displacement ductility of isolated bride piers. Furthermore, the isolator is more effective for more impactive earthquake motion such as Kobe record. It can be also seen that the utilization of contour diagrams on computer is very useful to identify the range of structural parameters which satisfy some restrictions on the nonlinear responses of isolated bridges.
Through this study, a two-step design procedure for seismically isolated bridges may be considered as
1) First, a non-isolated bridge with some displacement ductility of the pier for a design earthquake ground motion is preliminarily designed, 2) The parameters of isolator are then determined as the isolated bridges satisfy the restrictions on the damages to pier and isolator. This way may makes the assessment of effectiveness of isolation easy and be applicable to the retrofit of existing bridges.
At the moment, the analytical results obtained from this study have been limited. Additional research is needed to more fully evaluate the nonlinear interaction of isolated bridges for a wider range of ground motion and structural parameters.

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