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UNCERTAINTIES AFFECTING THE SEISMIC RELIABILITY OF RC BRIDGE PIERS

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SUMMARY

The need to replace conventional seismic design methods with a performance-based design system is well recognized. As such systems come into use around the world, reliability theory will be used for the safety evaluation of structures. In reliability-based design, it is important to identify critical uncertainties concerning structural safety and to adjust safety factors in order to attain a target safety level. In this study, the seismic reliability of reinforced concrete (RC) structures is considered in terms of a quantitative evaluation index *D* (e.g. failure probability or probable expected loss). In order to rank design uncertainties according to their effect on *D*, a flow chart is proposed based on system reliability theory and experimental design. This flow chart is then applied to RC bridge piers designed to previous and current specifications. By doing this, the change in seismic safety as well as the difference in the ranking of critical uncertainties associated with changing specifications can be evaluated.

INTRODUCTION

In the event of an earthquake, bridges and other transportation network structures must be used for civilian evacuation or for transportation of emergency supplies. Because of this, designers need to ensure the seismic reliability of these structures not only during an earthquake but also consider the damage level of these structures after an earthquake [1]. It is desirable that the failure probability of each structure in the network be close to the target failure probability [2]. This will cause equalization of seismic safety of these structures. To achieve this design, uncertainties in design parameters must be considered.

Since the Hyogo-ken-Nanbu earthquake (1995), while seismic analysis methods for RC structures have made great strides, many significant uncertainties remain, including the estimation of earthquake ground motions, soil parameters, etc. It is currently believed that the accuracy of dynamic analysis depends not on the choice of constitutive or analytical model, but input parameters such as soil conditions. However, there has been no way to quantitatively find uncertainties that affect the accuracy of dynamic analysis or seismic safety.

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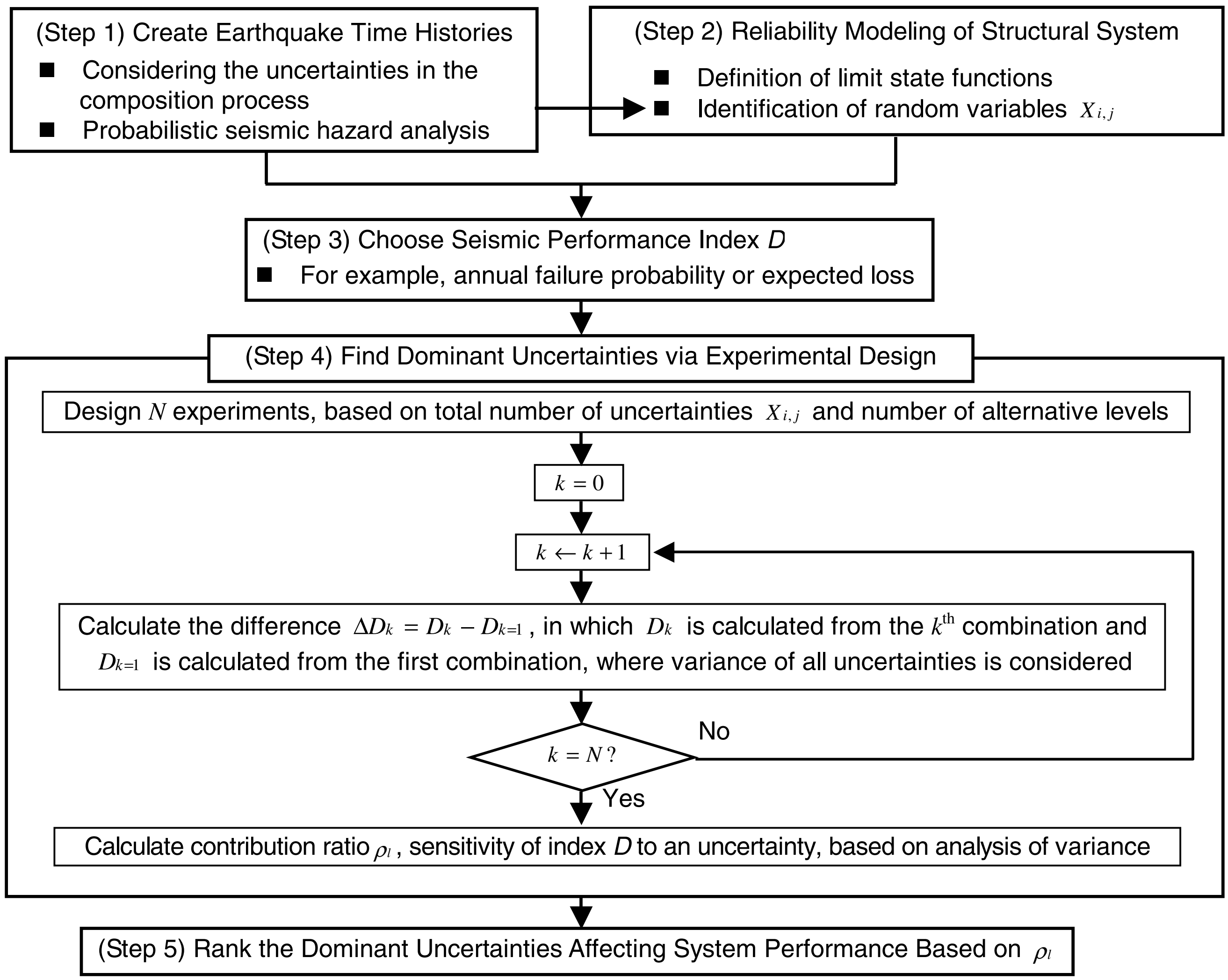

Figure 1. Finding Dominant Uncertainties Affecting Seismic Performance

Designers assess the impact of many variables when creating structures. If these uncertainties could be ranked according to their probabilistic significance, performance-based design would profit greatly. Earthquake engineers could focus their efforts, experimental or otherwise, on reducing the variability of critical uncertainties and allowing designers to create more rational and economical structures. For example, when a new material or structural type is adopted, it will naturally include some new uncertainties. By ranking these with other design variables and understanding the interaction of the whole, we can see if the reduction of their variability would yield greater safety. This permits the planning of experimental programs that economically evaluate the new material/system and maximize seismic safety when it is applied.

There are many indices used to express seismic safety, such as failure probability or probable expected loss. Based on system reliability theory and experimental design, a flow chart is proposed to rank the effect of individual uncertainties on this evaluation index. This flow chart is then applied to RC bridge piers designed to previous and current specifications. Using this technique, improvements seismic safety as well as differences between dominant uncertainties are studied across specifications.

FLOW CHART TO FIND DOMINANT UNCERTAINTIES WITH RESPECT TO SEISMIC SAFETY

When the seismic safety of a structural system is evaluated based on failure probability, seismic safety is quantified by annual failure probability p_f or conditional annual failure probability $P_{f,sys}(\alpha)$.

$$p_f = \int f_{ph}(\alpha) \cdot P_{f,sys}(\alpha) d\alpha \tag{1}$$

$$f_{ph}(\alpha) = -\frac{dp_0(\alpha)}{d\alpha} \tag{2}$$

where $p_0(\alpha)$ is the annual probability of exceedance, i.e. annual probability that the site intensity exceeds α ; and $P_{f,sys}(\alpha)$ is the conditional failure probability of a structural system in an earthquake of intensity α .

Figure 1 shows the flow chart proposed to rank the uncertainties with respect to their effect on seismic safety. This flow chart is described below in greater detail.

<Step 1>
The earthquake ground acceleration histories used in evaluation of seismic safety are created, quantified by probabilistic seismic hazard analysis. Uncertainties in this process are related to the calculation of $p_0(\alpha)$ or $P_{f,sys}(\alpha)$ in equation (1). The uncertainties to be considered depend on the method of seismic reliability analysis chosen. In the case of seismic reliability analysis based only on $P_{f,sys}(\alpha)$, uncertainties in the composition process of acceleration histories are reflected in the amplitude and phase characteristics of each history. For seismic reliability analysis based on p_f, uncertainties in $p_0(\alpha)$ need to be taken into account in addition to those relating to the history composition process.

<Step 2>
The model of the structural system to be studied is created. The following conditions need to be defined to calculate $P_{f,sys}(\alpha)$ based on structural system reliability.

The limit states of the structural system during and after an earthquake are identified, and their corresponding limit state functions are defined; e.g. g_i $(i = 1,2,\cdots,n)$ where n is the total number of limit states. $g_i > 0$ indicates a desirable outcome (safety state), and $g_i \leq 0$ indicates an undesirable outcome (failure state).

Uncertainties in limit state functions g_i are expressed as random variables $X_{i,j}(j = 1,2,\cdots,m_i)$ in which m_i is total number of random variables in limit state g_i. Each $X_{i,j}$ reflects one or several uncertainties. For example, the shear strength variable reflects the uncertainty in both the material strength and the shear strength equation.

<Step 3>
An index D to quantify the seismic safety is chosen: e.g. p_f, $P_{f,sys}(\alpha)$, probable expected loss, etc.

<Step 4>
The uncertainties affecting seismic safety are ranked based on the sensitivity of the index D to changes in variability of $X_{i,j}$. Here, this process is simplified by experimental design.
<Step 4-1>
In order to perform the ranking, a total of N sample experiments are designed. The number N is a function of how many variables are to be studied (L) and how many alternative levels each variable will take. For each experiment, each of the L variables is assigned a level, and the description of all experiments is

recorded in orthogonal arrays [3]. In the case study, only two alternative levels are considered: variance of an uncertainty is considered in level 0 and neglected in level 1.

<Step 4-2>

D_k is calculated as the seismic safety index (as chosen in Step 3) for the k^{th} combination in the orthogonal array. Then, the difference ΔD_k between D_k and D_1 $(2 \le k \le N)$ is calculated. Here, D_1 is D for the first experiment (k=1); it is the combination where the variance of all variables is considered.

$$\Delta D_k = D_k - D_{k=1} \quad (k = 2,3,\cdots,N) \tag{3}$$

If the number of variables L is large and ΔD_k is calculated for all possible permutations of levels 0 and 1, the computational effort required is immense. However, the arrays are devised to minimize N (see [3]).

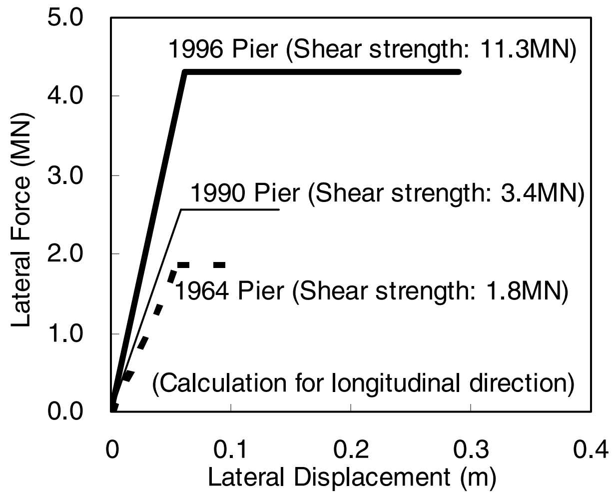

Figure 2. Relationship between Lateral Force and Displacement for Piers

<Step 4-3>

Contribution ratio ρ_l indicating the sensitivity of index D to each uncertainty is calculated based on a variance analysis.

<Step 5>

Dominant uncertainties affecting seismic safety of structural system are identified based on their contribution ratio ρ_l .

Advancements in computers make it easier to analyze the earthquake response of RC structures. Also, dynamic constitutive models of reinforced concrete have been presented. However, it is unclear whether these advantages have contributed to the reduction of annual failure probability. The effect of various uncertainties on $p_0(\alpha)$ or $P_{f,sys}(\alpha)$ is quantified in Figure 1, and the proposed flow chart provides information about uncertainties contributing the reduction of p_f.

At the present time, there are very large uncertainties in the Probabilistic Seismic Hazard Analysis process (PSHA, used in Step 1). It is difficult to estimate the variance of model parameters in PSHA based solely on databases of previous earthquakes and so on. However, if upper and lower limits for these parameters given by experts [4] are treated as uncertainties and incorporated in Figure 1, safety factors can be altered so as to prevent these uncertainties from affecting the seismic safety of structural systems.

FINDING THE DOMINANT UNCERTAINTIES AFFECTING THE SEISMIC SAFETY OF RC BRIDGE PIERS

The following section outlines an application of Figure 1. In this analysis, the change in seismic safety of RC bridge piers associated with different specifications is presented. Also, the flow chart is shown to be effective by studying the difference between the uncertainties that dominate the seismic safety of each pier.

RC Bridge Piers Adopted for Analysis

The three RC bridge piers used in this study were designed by Yoneda et al. [5]. These piers are designed according to different highway bridge specifications, revised in 1964, 1990, and 1996 (referred to as 1964

Pier, 1990 Pier and 1996 Pier, respectively). The ground condition at these piers is classified as Group II (moderate) [1]. The lateral force versus lateral displacement for each pier is shown in Figure 2.

Analytical Conditions

Earthquake ground motion analyzed

Probabilistic seismic hazard curves are calculated according to following conditions. In this example, the attenuation relationship proposed by Kawashima et al. [6] was used and its uncertainty is considered. However, the difference between Kawashima's attenuation relationship and those of other researchers is neglected. Note that:

a) Osaka, Japan was selected as the site for this illustrative case study. The earthquake history information used was that presented by Kameda and Nojima [7].
b) The intensity α is considered to be the peak ground acceleration α_g, and the Group II soil attenuation relationship proposed by Kawashima et al. [6] was used.

Figure 3 shows seismic hazard curves obtained from the above conditions. Another curve, not considering attenuation uncertainty [6], is also shown in Figure 3. Since the effect of attenuation uncertainty is also included in this study, the latter curve is used to calculate p_f when the variance of H is not to be considered

The acceleration histories ($\alpha = \alpha_g$) are simulated based on the method and conditions (a)-(c) proposed by Sato et al. [8]. These simulated ground motions are created in accordance with following conditions.

a) The number of simulated ground motions for each α_g is one hundred.
b) The duration of each history is 60 seconds.
c) Phase characteristics are calculated using an arbitrary combination of magnitude $6.5 \le M \le 8.0$ and epicentral distance $10 \le \Delta \le 50$ km.

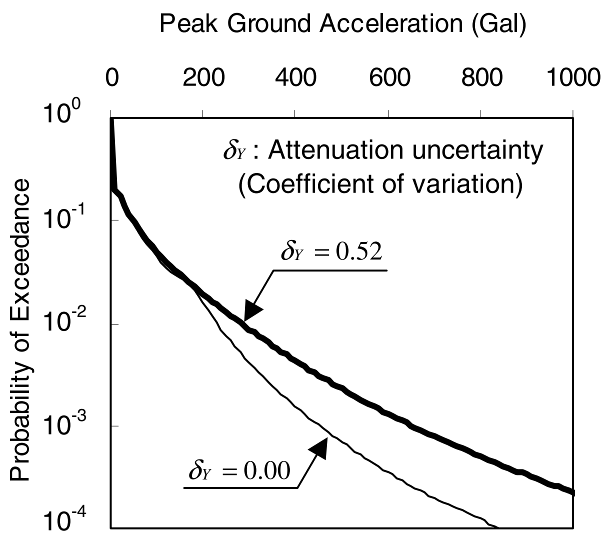

Figure 3. Example of Seismic Hazard Curve

Each history is scaled to a design spectrum (according to the highway bridge specification) for soil Group II (moderate) [1] and average acceleration $\overline{\alpha_g}$ for one hundred motions is calculated. Simulated ground motions multiplied by $\alpha_g / \overline{\alpha_g}$ are used in the time history response analysis of bridges for peak ground acceleration α_g.

Uncertainty in phase characteristics is simply considered in the Japanese seismic highway bridge specification. The average bridge pier response is calculated by time history response analysis using only three design ground motions. To examine the effect of this simple consideration on seismic safety evaluation of an RC bridge pier, we set two levels (level 0 and level 1) for uncertainty of phase characteristics. For level 0, bridge pier response is calculated by three simulated ground motions chosen randomly from one hundred simulations, and that average is used for the system reliability analysis described in following section. The coefficient of variation is assumed to be 0%. For level 1, bridge pier response is calculated using one hundred simulated ground motions. The average and actual coefficient of variation are used for $P_{f,sys}(\alpha)$.

Currently, there are various methods to create probabilistic seismic hazard curve or to simulate the ground motions to α_g. In future, the effect of uncertainties on p_f not considered above must be studied. For example, uncertainties in source definition, location and geometry, maximum magnitude, recurrence rates and choice of attenuation relations.

Condition of system reliability analysis of RC bridge pier

In the reliability analysis of an RC bridge pier, many design variables, such as shear strength, flexural strength, etc., need to be taken into consideration, regardless of the failure mode. In this study, $P_{f,sys}(\alpha)$ in equation (1) is calculated as in reference [9]. For a bridge pier, limit state functions g_i include shear failure, ductility, and residual displacement in the longitudinal and transverse directions. $P_{f,sys}(\alpha)$ represents the probability that one or more of the limit state equations is below zero (g_i <0). The parameters of the probability variables used in calculation of $P_{f,sys}(\alpha)$ are the same as reference [9].

Uncertainties involved in seismic design of RC bridge pier

The uncertainties involved in the seismic design of an RC bridge pier (i.e. those used in this study) are listed in Table 1.

Dominant uncertainties affecting the seismic safety of RC bridge pier

In this study, p_f is used to quantify the seismic safety (D). Figure 4 shows the conditional annual failure probability of each pier under simulated ground motion with peak ground acceleration α_g . As stated, this reliability analysis takes all failure modes/limit states into account. The seismic safety level of the 1996 Pier is higher than that of the 1964 Pier. This reflects the lateral force versus displacement relationships seen in Figure 2. Since the 1964 Pier is so weak in shear, $P_{f,sys}(\alpha)$ for the 1964 Pier is approximately the same as the shear failure probability for all α_g . On the other hand, $P_{f,sys}(\alpha)$ of the 1996 Pier is approximately equal to the failure probability with respect to ductility if α_g < 400 Gal , with respect to residual displacement if 400 < α_g < 650 Gal, and with respect to both ductility and residual displacement when α_g >650 Gal. Clearly, the limit state governing the failure probability of a structural system may differ depending on the magnitude of the earthquake simulation. This needs to be taken into consideration when failure probabilities of structural systems are calculated using an earthquake of arbitrary magnitude.

Table 1. Uncertainties Involved in Seismic Design of RC Pier

Uncertainties in material strength	
Shear capacity of concrete	V_c
Shear capacity of steel	V_s
Flexural capacity	V_{act}
Ultimate displacement	δ_u
Yielding displacement	δ_y
Uncertainties in shear strength and ultimate displacement equations	
Shear capacity of concrete	α_3
Shear capacity of steel	α_2
Ultimate displacement	α_4
Uncertainties in structural analysis	
Shear force	α_3
Residual displacement	C_R
Uncertainties in seismic hazard evaluation	
Response displacement	δ_{pd}
Attenuation uncertainty	H

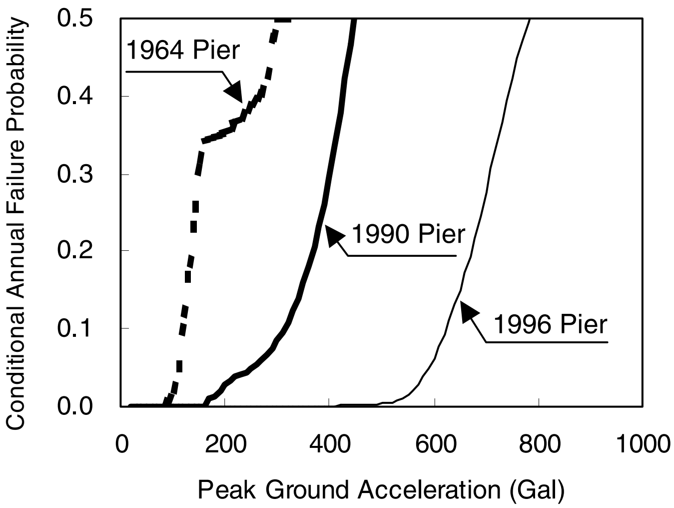

Figure 4. Conditional annual failure probability: piers subjected to simulated ground motion

Figure 5 shows annual failure probability of RC bridge piers under the simulated ground motions calculated using Figure 3 and Figure 4. p_f (of equation (1)) values for the three piers, obtained by integration of failure probabilities in Figure 5, are listed in Table 2. It is confirmed in Table 2 that (a) the seismic safety of RC bridge piers has significantly increased with recent specifications; and (b) even though annual failure probability depends on an assumption to obtain a probabilistic seismic hazard curve, p_f of 1996 Pier according to the current specifications of highway bridges is more or less the same as that of an underground RC structure reported by Motegi et al. [10]. This shows that by using this technique, it is possible to establish new seismic specifications equalizing the seismic safety, independent of design requirements or structural type.

Finally, the dominant uncertainties affecting seismic safety are listed in Table 3. For each pier, the sum of the contribution ratios ρ_l shown in Table 3 (except "others") is over 90%. Uncertainties having a significant effect on seismic safety based on the magnitude of their contribution ratio, accurately reflect each pier's characteristics. For example: as shown in Figure 3, attenuation uncertainty (H) has no effect on p_0 for low α_g . Since $P_{f,sys}(\alpha)$ for the 1964 Pier increases in this region, the uncertainty H does not play any role. Because the 1964 Pier is very weak in shear, uncertainty in shear force obtained from dynamic analysis α_3 clearly has a great effect on the seismic safety of pier.

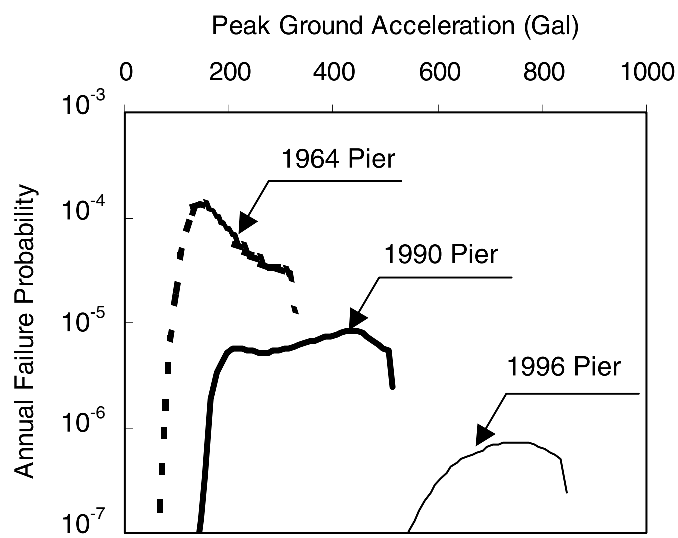

Figure 5. Annual Failure Probability of RC Pier

Table 2. Annual Failure Probabilities

1964 Pier	1990 Pier	1996 Pier
1.6×10^{-3}	2.2×10^{-4}	1.7×10^{-5}

In the case of 1996 Pier, it is confirmed that a) as shown in Figure 3 and Figure 4, because $P_{f,sys}(\alpha)$ increases in the range of acceleration where the magnitude of $p_0(\alpha)$ depends on attenuation uncertainty H, H has a great effect on p_f; b) since the pier undergoes inelastic response when the annual failure probability $f_{ph}(\alpha)P_{f,sys}(\alpha)$ shown in Figure 5 is higher, uncertainties δ_{pd} and C_R associated with limit states of ductility and residual displacement have effect of seismic safety of pier, and c) uncertainties in material strength are insignificant. Thus, using the flow chart in Figure 1, dominant uncertainties affecting seismic safety of piers can be found and we can gather information to improve seismic safety.

Table 3. Dominant Uncertainties Affecting the Seismic Safety of RC Pier

Order	1964 Pier		1990 Pier		1996 Pier	
	Uncertainty	ρ_l	Uncertainty	ρ_l	Uncertainty	ρ_l
1	α_3	84%	α_4	74%	H	35%
2	α_4	7.3%	α_3	11%	C_R	33%
3	Others	8.7%	δ_{pd}	8.0%	δ_{pd}	11%
4	---	---	Others	4.0%	α_3	9.5%
5	---	---	---	---	α_4	3.6%

The designer cannot respond to uncertainties using only their contribution ratio ρ_l, which shows only the magnitude of the effect. The case study shows that, for example, δ_{pd} has a significant effect on the seismic safety of the 1996 Pier. This suggests that designers should consider both the mean and the variance of this variable. If the value of δ_{pd} is calculated using only 3 earthquake time histories (like the Japanese seismic highway bridge specification requires), the designer may not have a sufficient grasp on the variance and its effect on seismic safety. Therefore, in order to attain the target reliability, the safety factor used in the design should depend on the number of simulated earthquake time histories. This issue will be addressed in future research.

CONCLUSIONS

In this study, seismic safety was quantified by evaluation indices such as failure probability and expected loss. A flow chart to rank the uncertainties affecting these indices was proposed based on system reliability theory and experimental design.

This flow chart was then applied to RC bridge piers designed according to previous and current specifications (1964, 1990, and 1996). The increase in seismic safety of RC bridge piers associated with newer specifications was evaluated in terms of probability theory. Finally, the differences between the critical uncertainties of each pier were studied based on the proposed flow chart. It was confirmed that the flow chart yielded information that would allow a designer to identify dominant uncertainties in a design and effectively improve the safety of such a design.

In future research, this flow chart will be applied to many systems, including RC bridges with pile foundations. Also, more recent probabilistic seismic hazard analysis methods will be applied in order to evaluate uncertainties that were not considered in this study (e.g. fault length and angle).

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