State of the Art in Input Ground Motions for Seismic Fragility and Risk Assessment

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1. Introduction

The purpose of a Seismic Probabilistic Safety Analysis (SPSA) is to determine the probability distribution of core damage due to the potential effects of earthquakes. The SPSA is performed based on four steps, a seismic hazard analysis, a component fragility evaluation, a plant system and accident sequence analysis, and a consequence analysis. A seismic fragility evaluation is used to estimate the conditional probability of a failure of important structures and equipment whose failure may lead to unacceptable damage to a plant. The component fragilities are needed in a SPSA to estimate the conditional probability of an occurrence of initiating events as well as the conditional failure probabilities of different mitigating systems.

There are very different spectrum shapes in every ground motions. The structural response and the seismic load applied to equipment are greatly influenced by a spectral shape of the input ground motion. Therefore the input ground motion need to be determined under the same assumption in risk calculation. Several technics for the determination of input ground motions has developed and reviewed in this study.

2. Seismic Risk and Fragility Curve

2.1 Risk Equation

The plant damage state frequency is obtained by convolving plant level fragilities with the seismic hazard curves. The probability distribution for the unconditional frequency of core damage can be obtained through Eq. (1).

$$P_f = \int_0^\infty H(a)\left(\frac{dF(a)}{da}\right)da = \int_0^\infty F(a)\left(\frac{dH(a)}{da}\right)da \quad (1)$$

where, $H(a)$ represents the seismic hazard curve, and $F(a)$ represents the plant level fragility curve. This equation is called risk equation.

Fragility curve is expressed as a probability of failure versus intensity of ground motion parameter inducing damage. For an earthquake event, these intensity parameters are used to be a spectral acceleration or a peak ground acceleration. The fragility curve of a component is modeled as a cumulative lognormal distribution along the intensity parameter. Accordingly fragility curve can be defined by median ground acceleration capacity, and two logarithmic standard deviations as expressed in Equation (2).

$$F(a) = \Phi\left[\frac{\ln(a) - \ln(A_m) + \beta_U \Phi^{-1}(Q)}{\beta_R}\right] \quad (2)$$

where, Φ denotes standard Gaussian cumulative distribution function and A_m is a median ground acceleration capacity. Two logarithmic standard deviations represent different kinds of uncertainty. One is a deviation of inherent randomness, β_R, and the other is a deviation of uncertainty, β_U. And the non-exceeding probability level of the median value, Q is introduced to consider the uncertainty in this equation.

A hazard curve can be represented as annual frequency of exceedance curve which decreases linearly with regard to the seismic intensity in a log-scale graph. The standard deviation of a fragility curve can be represented by single parameter β_C, which is square root of sum of β_R and β_U squares. Then the risk equation has closed form solution as in Eq. (3)

$$P_F = \gamma(a^*) f_s^{-K_H} \exp\left[-x_p K_H \beta_c + \frac{1}{2}(K_H \beta_c)^2\right] \quad (3)$$

where, K_H denote the slope of hazard curve.

In this equation, the risk increases as the standard deviation of fragility curve increases. Therefore all possible uncertainties should be included in the fragility curve. The risk value is calculated in realistic manner. It means the conservatism in component failure probability should be removed. Therefore, the input ground motion need to be determined considering these two respect.

3. Input Ground Motion Determination Methodologies

3.1 Generic Response Spectrum

In early SPSA, the fragility curve was derived using the design response spectrum or certified response spectrum such as RG 1.60 spectrum or NUREG-0098 spectrum. In this case, the spectral shape does not represent the site specific conditions. Its uncertainty needs to be included in seismic fragility curve. The standard deviation of this uncertainty is relatively large [1], so, the risk value can be high.

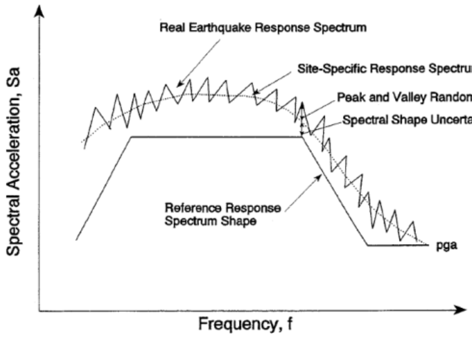

Fig. 1. Spectral shape uncertainty [1]

3.2 Uniform Hazard Spectrum

In recent SPSA, the spectral shape of input ground motion is determined as the uniform hazard spectrum. The spectral acceleration in this spectrum has same annual exceedance frequency in every frequency point. It means than the hazard curve defined by peak ground acceleration can be used with risk consistency whatever the structural natural frequency be.

3.3 Conditional Mean Spectrum

The uniform response spectrum still has conservatism because the annual frequency value in seismic hazard curve is the sum of the marginal probability in the distribution of an attenuation equation, epsilon. It means that the input ground motion of which the spectral acceleration corresponds to the uniform hazard curve is very rare if the spectral acceleration is not correlated in each frequency points. The conditional mean spectrum can be used to consistent annual exceedance frequency with hazard curve [2].

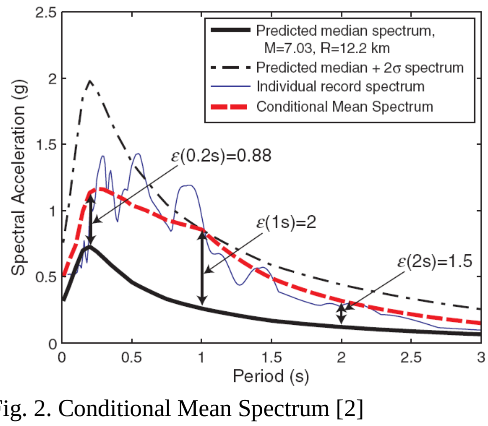

Fig. 2. Conditional Mean Spectrum [2]

3.4 Time History Generation by Using Seed Motion

The uncertainty caused by time history characteristics does not appear in a spectral shape. To consider this in realistic way, the input ground motion time history need to be selected as recorded ground motion. But in this case, the spectrum shape will be different from the uniform hazard spectrum or the conditional mean spectrum. Therefore, target response spectrum matching technics in time domain is necessary [3]. By this method, the seed motion which is the recorded ground motion can be modified to spectrum compatible ground motion time history.

3.5 Bi-directional Motion

The intensity of the ground motion in a seismic hazard curve is represented as spectral acceleration. In the hazard analysis, a ground motion attenuation equation which represents the relation between an earthquake moment magnitude, a distance to the site, and a spectral acceleration is used. This equation is estimated by the regression analysis based on the spectral acceleration from the observed seismograms. The spectral acceleration of an accelerogram has no uncertainty itself. However this spectral acceleration has two values in one location in each orthogonal horizontal direction when earthquake vibration occurs. Not only the peak acceleration, but also the spectral acceleration is different in a direction. It means that the seismic hazard curve ignores the randomness of directional intensity which can increase the standard deviation of fragility curves. This uncertainty can be evaluated by the comparison of geometric mean spectral acceleration [4] and maximum directional spectral acceleration. The input ground motion need to be scaled considering this uncertainty distribution.

4. Conclusions

In this research, the methodologies of the determination of input ground motion for the seismic risk assessment are reviewed and discussed. It has developed to reduce the uncertainty in fragility curves and to remove the conservatism in risk values.

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