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A SIMPLE MODEL FOR ANALYZING SEISMIC PERFORMANCE OF TALL BUILDINGS OF REINFORCED CONCRETE

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SUMMARY

This paper presents a framework for developing damage probability plots showing the seismic performance of tall buildings subject to various seismic excitations. The damage plots indicate structural performance in terms of magnitude, source mechanism, epi-central distance and site condition; and such probability plots are more comprehensive, specific and useful than the traditional vulnerability plots in terms of peak ground acceleration or macroseismic intensity. The focal mechanism can be of strike-slip, reverse-slip or unspecified faulting types. The path effect or near and far field effect can be investigated independently as the vulnerability is now expressed in terms of epi-central distance. The fragility curves can also be specified for a given magnitude versus various epi-central distances. Location specific site condition can also be examined. Therefore, a more reliable prediction of probable damages can be made for scenario earthquake analysis. In contrast to the existing push-over technique, the seismic response of the building is obtained through modal superposition method, incorporating the effect of higher mode effects. The procedure is illustrated by using a typical 21-story reinforced concrete building of Mei Foo Sun Chuen in Hong Kong. With this approach, the probable damages of any building can be estimated with higher confidence. Consequently, a more reliable risk assessment and a more cost-effective retrofitting can be decided.

Key words: tall building, magnitude, distance, site condition, damage probability surfaces.

INTRODUCTION

Seismic hazard analyses involve quantitative estimation of ground shaking at a particular site. Seismic hazards may be analyzed either deterministically, when a scenario earthquake is assumed, or probabilistically, when uncertainties exits in assigning earthquake magnitude, location and frequency. For important structures or buildings, a site-specific hazard may be needed by incorporating the source

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characteristics of scenario earthquake (including both magnitude and epi-central distance). Recently, probabilistic ideas have also been incorporated in evaluating hazard due to scenario earthquakes.

In the traditional deterministic method, seismic hazard is specified by probability of occurrence of an earthquake, within a specific period of time, at a particular site or in a given area. In recent years, a new approach called "disaggregation of probabilistic hazard analysis" has been proposed, and in essence seismic hazard is expressed in terms of magnitude for a specific source zones (i.e. fixed epi-central distance). The beauty of this approach is that relative contributions of the estimated hazard can be evaluated for various earthquake magnitudes, source-to-site distances, and uncertainties in the attenuation law. This approach, that seismic hazard is obtained separately for each fault and these results are successively combined for all faults in a region, is called "disaggregation of probabilistic seismic hazard analysis" [1,2]. It offers an approach that can identify the most likely earthquake scenarios contributing to hazard and can express contribution to site hazard as a function of magnitude and/or distance by magnitude-distance. Consequently, "fault-specific" ground motion can be picked for time history analysis for structural vulnerability analysis since hazard-dominating scenario events can be identified. However, the latter part of works in assessing structural vulnerability is still in its infancy.

Further development of the idea of disaggregation of seismic hazard is being actively engaged. One potential extension or advance in this direction is to connect damage probability directly to seismic source, travel path, and site condition rather than using the traditional input parameters of peak ground acceleration (PGA) or macroseismic intensity (I). The ultimate goal is to produce damage-probability or fragility curves of a class of buildings in terms of these source characteristics, magnitude, epi-central distance, and site condition. Empirical approach has been used to relate building damages directly to magnitude and distance from an earthquake. Initial efforts to establish such empirical relations are under way using data from earthquake records [3-6]. A tentative damage ratio attenuation relation is put forward in Iceland, expressing in terms of epi-central distance for earthquake magnitude within 6.25-6.5 [7]. Clearly, to well estimate any of such relationships on the basis of observed building damages, a substantial amount of data is required. Unfortunately for earthquake engineers (or fortunately for most people), large earthquakes do not occur regularly. An alternative is to establish the building vulnerability based on analytical methods. Such a method will be developed in this paper. In particular, damage probability distributions among various damage states are established for a spectrum of earthquakes, specified by magnitude, epi-central distance, and soil condition in this study.

Another main concern of the present study is to propose a more reliable but yet simple approximate method for evaluating the seismic performance of tall or high-rise buildings. Despite that numerous dramatic collapses have occurred at mid or upper sections of tall buildings during earthquakes in Mexico City in 1985 and in Kobe in 1995, a realistic approximate method that would be used to evaluate localized story collapse due to higher mode oscillations of buildings is still absent for vulnerability analysis [8]. Most up-to-date seismic damage probability assessment procedures are based on the first mode response of a building such that equivalent static forces can be assumed to distributed in manner typically occurring during first mode response (such as HAZUS methodology adopted in USA and Yin's simplified inelastic method adopted in China [9,10,11]). The HAZUS methodology is a loss estimation method based upon push-over response of an equivalent single degree of freedom oscillator. On the other hand, the methodology of Yin's simplified vulnerability analysis is based upon an equivalent lateral forced method for a multi-degree-of-freedom-oscillator. Simplified inelastic approach is used to estimate damages in terms of the value of ductility distribution of a certain class of buildings. These methods have mainly been used for seismic evaluation of low-to-mid rise structures for which the response is primarily characterized by the fundamental mode of vibration. They can be inadequate for structures with significant higher mode response. In this paper, analysis method is extended to include the effects of potential mid-story failure mechanisms by adopting the modal analysis of multi-degree-of-freedom-oscillator; and, at the same time,

the damage probability distributions is expressed in terms of magnitude and epi-central distance, with due account for site condition.

METHODOLOGY OF PROBABILISTIC DAMAGE ANALYSIS

Input source-path-site: seismological parameters and site parameter

As mentioned earlier, in this paper site hazard is expressed in terms of both source parameters (such as, earthquake magnitude and epi-central distance) and site parameter (such as, soil condition). With these input, seismic performance of any building is then calculated. One simple way to incorporate all these factors is to use a simple attenuation relation of the spectral acceleration in terms these various factors. In this study, the attenuation relation developed by Boore et al. [12] is used to demonstrate the effects of source, travel path, and site condition on damage probability distribution for a typical tall building of reinforced concrete in Hong Kong. More specifically, Boore et al. [12] proposed the following spectral acceleration S_a as function of natural period of the structure, earthquake moment magnitude M, epi-central distance r, and site condition as:

$$\ln S_a(T) = b_1 + b_2(M-6) + b_3(M-6)^2 + b_5 \ln r + b_v \ln \frac{V_S}{V_A} \tag{1}$$

where

$$r = \sqrt{r_{jb}^2 + h^2} \tag{2}$$

and

$$b_1 = \begin{cases} b_{1SS} & \text{for strike - slip earthquakes;} \\ b_{1RS} & \text{for reverese - slip earthquakes;} \\ b_{1ALL} & \text{if mechansism is not specified} \end{cases} \tag{3}$$

In this equation $S_a(T)$ is the pseudo-acceleration response in g; M is the moment magnitude, r_{jb} is the distance in km, and V_s is the average shear-wave velocity of the top 30 m of soil or rock in m/sec. Coefficients to be determined are $b_{1SS}, b_{1RS}, b_{1ALL}, b_2, b_3, b_5$, h, and V_A. Clearly these equations include the effect of fault mechanism and site conditions. Note that the source mechanisms are classified as strike-slip, reverse-slip, or unspecified faulting mechanisms.

The main purpose of this paper is to analyze the effects of magnitude, source mechanism, epi-central distance, and site condition on probability distribution of damage among the different damage states; thus,

Eqs. (1-3) can be used to demonstrate these effects. The seismic performance for tall buildings will be discussed next.

Estimation of inelastic seismic response of multistory buildings

As remarked in the Introduction, in this paper inelastic seismic performance of multistory structures under seismic conditions is assessed using spectral modal analysis for multi-degree-of-freedom system. Once the structural response is estimated, the probable ductility response and in turn damages can be evaluated.

The tall building is modeled as multi-degree-of-freedom system. It is assumed that the mass of the structure is lumped at the center of mass of each story level. The seismic actions on the buildings are assumed taken by lateral resisting structural elements (i.e. columns and shear walls).

The modal lateral force F_{xm} of the m-th mode at the level x of the building subject to horizontal motion along one axis is then given by

$$F_{xm} = \frac{\sum_{i=1}^{N} W_i \phi_{im}}{\sum_{i=1}^{N} W_i \phi_{im}^2} \phi_{xm} S_a(T_m) W_x \tag{4}$$

in which $S_a(T_m)$ is the spectral acceleration (in unit of g) corresponding to a natural period T_m of the m-th mode of vibration, and W_i and W_x are the weight attributed to the level i and x of the building respectively. The m-th mode shape value at the x-th level of the building is denoted by ϕ_{xm}.

The modal shear force V_{xm} at level x is given by summing all seismic forces of upper stories:

$$V_{xm} = \sum_{i=x}^{N} F_{im} \tag{5}$$

All the significant modes of vibration should be included when the dynamic response is estimated. Because of the prevailing contribution of the first few modes to the response of the structures, the response of most buildings is estimated mainly by the superposition of the first few modes of vibrations. There are various ways to combine the effect of different modes. A simple approach is the use of SRSS (square root of the sum of squares) method, but this method is not good for buildings with natural frequencies very close to each other (i.e. inter-mode coupling may occur). However, for normal multi-story buildings, SRSS should be an efficient yet reliable method to estimate the seismic shear force acting on a structure. In particular, the maximum seismic shear at the x-th story of a building can be estimated by

$$V_x = \sqrt{\sum_{m=1}^{j} V_{xm}^2} \tag{6}$$

A more accurate procedure, the 'complete quadratic combination' CQC may also be adopted, but such method is computationally more demanding. One should also note that this modal analysis approach assumes implicitly that the building responds elastically or in other words there is no inelastic deformation occurring in the building.

Once the seismic shear estimated from Eq. (6) exceeds the elastic yield shear force at any story of the building, inelastic deformations set in. Then, local damages at a particular story occur. A simple way to quantify the degree of story damages is to define a mean story yield shear coefficient can be defined as

$$R = \frac{Q_{yx}}{V_x} \tag{7}$$

where Q_{yx} is the yield shear of the *x*-th story. For reinforced concrete buildings, the yield shear can be estimated as

$$Q_{yx} = 0.2 F_C A_{wx} \tag{8}$$

In Eq. (8), F_C is the compressive strength of concrete and A_{wx} is the total sectional area of columns and shear walls which are parallel to the earthquake action in the *x*-th story. Many studies show that, in the case of multi-story frame structures with shear walls, non-linear deformation will concentrate at the weakest stories [13,14], which correspond to the minimum *R* in Eq. (7). Note also that in the calculation of V_x, the dynamic characteristics of the ground motions have been taken into account approximately through the use of S_a from Eq. (1). Thus, the yield shear coefficient given in Eq. (7) relates not only to the strength of the building, but also to the characteristics of the seismic input. A limitation of this approach is that we cannot consider the local damage of a particular column or wall, and only the overall average damage is considered.

The maximum story ductility factor is a key parameter indicating building damage. The story with minimum yield shear coefficient experiences the maximum deflection and attains the maximum ductility factor. The ductility factor is defined as ratio of the deflection of a building on specified soil condition subject to a specified earthquake to the maximum elastic deflection of the building at a particular story. When a building is subject to small or moderate earthquakes, ductility will be smaller than one. When a building is subject to strong earthquakes, damages occur and ductility will be larger than one. Since energy has to be dissipated through the building damages, energy consideration can lead to the estimated of maximum deflection or in turn the maximum ductility. Without going through the details, the following formula for the maximum mean ductility factor μ_0 of frame-wall buildings can be obtained:

$$\mu_0 = \begin{cases} \dfrac{1+R^2}{2R^2} & R \le 1 \\ \dfrac{1}{R} & R > 1 \end{cases} \tag{9}$$

where R is the minimum yield story shear coefficient calculated for Eq. (7). This formula can further be refined by adding correction factors C_i to the maximum mean ductility factor:

$$\bar{\mu} = \mu_0 \left(1 + \sum C_i\right) \tag{10}$$

In traditional vulnerability analysis of buildings, a simple model is used to estimate the seismic performance for classes of buildings instead of individual buildings. Ideally, buildings in the same class should be of similar story numbers, made of similar materials, composed of similar structural forms, and most importantly should behave in a similar manner under seismic excitations. In reality, there must be some variations in the structural responses, leading to various damage states. Further, buildings in the same class may behave similarly during one particular earthquake, but may behave in a completely different manner during another. In view of this, probabilistic or stochastic approach is commonly adopted. Thus, ductility as well as damage state of a class of building under a specific scenario earthquake is better represented in terms of probability functions. Numerous field observations after major earthquakes demonstrate that damages in buildings of the same class satisfy a lognormal probability distribution. Thus, ductility may also be expressed in lognormal distribution. More specifically, probability density function of ductility can be estimated as:

$$f(\mu) = \frac{1}{\sqrt{2\pi}\xi\mu} \exp\left[-\frac{(\ln\mu - \lambda)^2}{2\xi^2}\right] \tag{11}$$

where

$$\lambda = \ln\bar{\mu} - \frac{1}{2}\xi^2, \qquad \xi^2 = \ln\left(1 + \frac{\sigma^2}{\bar{\mu}^2}\right) \tag{12}$$

In these equations, $\bar{\mu}$ and σ are, respectively, the maximum mean value estimated from Eq. (10) and standard deviation of ductility factor of the story. In this study we assume that the main uncertainty is from ground motion input and the value of $\sigma/\bar{\mu}$ is deduced from the uncertainty of the attenuation relationship used.

Damage probability distribution

When seismic hazards are expressed in terms of macroseismic intensity or peak ground acceleration (PGA), the vulnerability is expressed in terms of the damage probability matrix (DPM) or fragility curves. However, for disaggregation of seismic hazard, three-dimensional plots of hazard versus magnitude and epi-central distance are commonly used (e,g, [1] and [15]).

Five damage states, namely undamaged, slightly damaged, moderately damaged, extensively damaged, and completely damage states are adopted. For buildings with frame and walls, the threshold ductility factors for the onset of slightly damaged, moderately damaged, extensively damaged and completely damaged states can be established as 1.0, 1.5, 3.0 and 5, respectively [11]. Using these threshold values as

the limits of integration, the probability of various damage states for a given earthquake (specified magnitude and source faulting mechanism) can be integrated as:

$$P\left[D_j \middle| M, R, SI\right] = \int_{\mu_j}^{\mu_{j+1}} \frac{1}{\xi\mu\sqrt{2\pi}} \exp\left[\frac{-(\ln\mu - \lambda)^2}{2\xi^2}\right] d\mu \qquad (13)$$

where μ_j and μ_{j+1} are respectively the threshold of ductility factor for the onset of damage states D_j and D_{j+1}.

To separate or so-called disaggregate the effect of epi-central distance from the total hazard, a new distribution curves representing the non-exceeding (equal or less) probability for a damage state D_i is defined as $P\left[D \le D_i \middle| R, M = M_0\right]$. These curves can demonstrate the geographical extent and spatial distribution of building damage for buildings on a particular site condition subject to a specific event. To single out the effect of magnitude from the total hazard, another type of fragility curves representing the non-exceeding probability for a damage state D_i can be defined as $P\left[D \ge D_i \middle| M, R = R_0\right]$. It indicates the effect of seismic source characteristics on building damages. With the help of these plots, the effects of site condition and source faulting mechanism on damage distribution of buildings can be evaluated at a given distance and with a given magnitude.

ILLUSTRATIVE EXMAPLE

One 21-story RC frame/shear wall building in Hong Kong is chosen for our case study. The structural plan of the columns and shear walls for the typical storey of the upper level is shown in Fig 1.

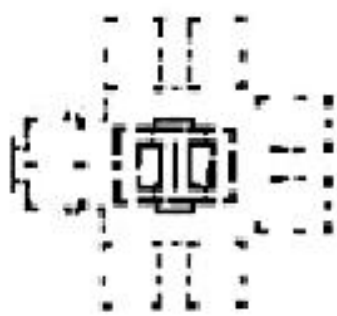

Fig.1. The plan section of the columns and shear walls of the buildings.

The occurrence probability distributions of damage among the different damage states of the building situated on rock site (NEHRP class V_s = 620 m/sec) condition and for source mechanism unspecified are illustrated in Figs. 2(b-f) for the five damage states of intact state, slightly damage state, moderately damage state, extensively damage state, and completely damage state, respectively. In this example, only the four modes of vibrations are included in the modal analysis.

At a distance of 15 km from the epi-center of the earthquake, the fragility curves on rock (NEHRP class V_s = 620 m/sec) and source mechanism unspecified are presented in Fig. 3(a). It is apparent that the increase in magnitude leads to a marked increase in the exceeding probability for all five damage states. The

effects of site conditions on the probability distribution of damage are given in Fig. 3(b), showing the exceeding probability for damage states at both a soil site (V_s = 310 m/sec) and a rock site (V_s = 620 m/sec) at 15 km. It can be seen that the effect of site condition is very significant. To compare the effects of seismic source mechanism, Fig. 3(c) plots the exceeding probability for different damage states induced by strike-slip event, reverse-slip event, and mechanism unspecified event at rock site at 15 km from the epi-center. As shown in Fig. 3(c), source mechanism is relatively less significant comparing to effects of magnitude and site condition.

To demonstrate the effect of epi-central distance, Fig. 4(a) shows the damage probability distributions for the 21-story building situated at rock site (V_s = 620 m/sec) when an earthquake with moment magnitude of 6.5 occurs. The source mechanism is chosen as unspecified. It can be seen that damages attenuate rapidly with distance. To illustrate the effects of site conditions, Fig. 4(b) shows the damage probability (non-exceeding probability) curves for the 21-story building situated at NEHRP site class C (V_s = 520 m/sec) and class D (V_s = 250 m/sec). It is clear that damage of the same building at site class D is much more severe than that at site class C. Therefore, the local site condition at which the building is located is of paramount importance. Therefore, high-rise or tall buildings are more conducive to seismic damage if the building is on soft ground and the earthquake is a far-field one. Figure 4(c) compares the damage probability distributions at rock site (V_s = 620 m/sec) for a moment magnitude of 6.5 for various source mechanisms (i.e. strike-slip, reverse-slip, or mechanism unspecified). As expected, the effect of earthquake source mechanisms on damage probability distribution is much less significant than the effects of site conditions and epi-central distance

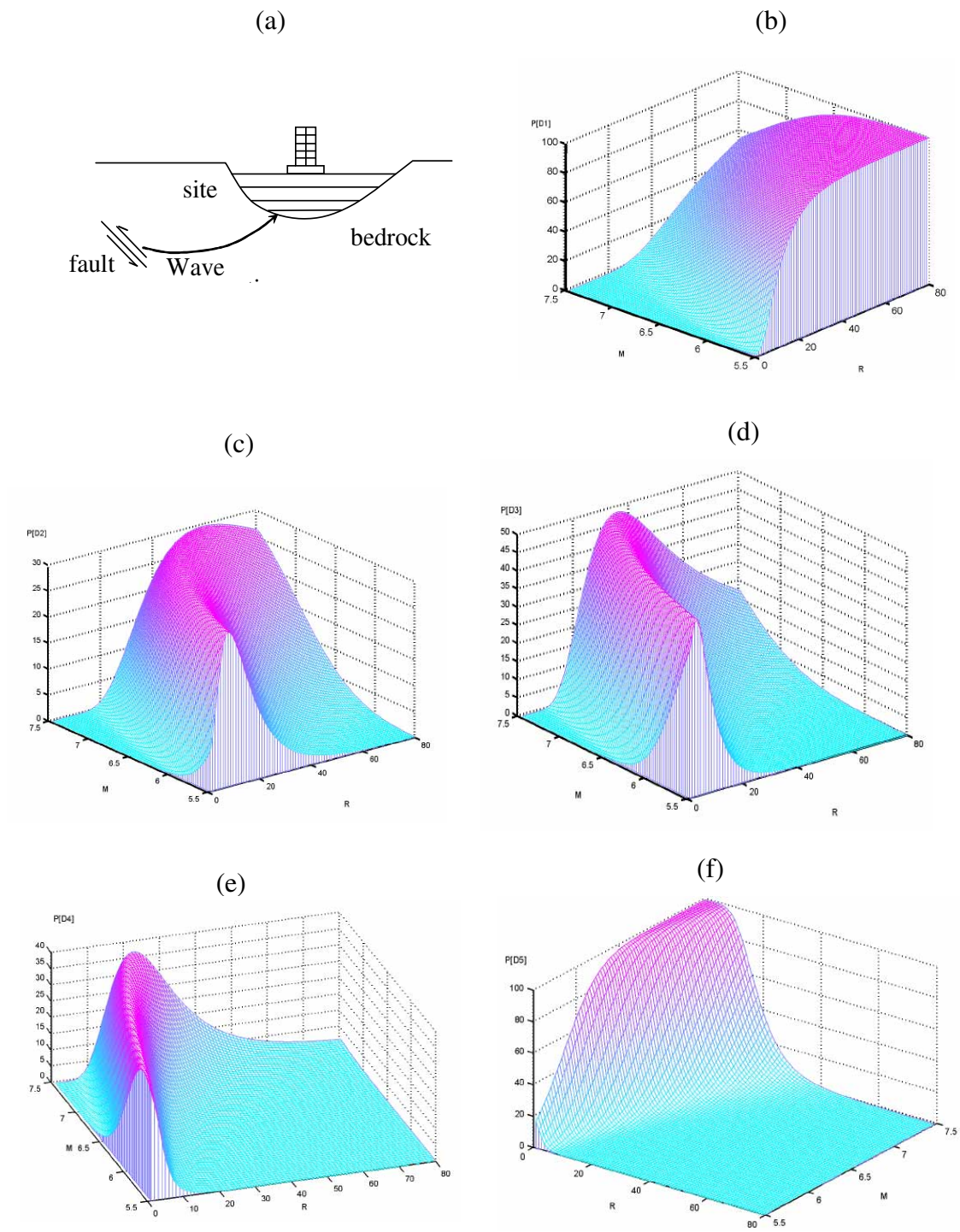

Fig.2. (a) Schematic figure showing the effects of seismic source, propagation path and site condition on damage. (b), (c), (d), (e) and (f): The probability of occurrence for intact state, slight damage, moderate damage, extensive damage, and complete collapse (i.e.D_1,D_2,D_3,D_4, and D_5) defined in terms of earthquake characteristics- as function of moment magnitude *M* and epi-central distance *R* (km) on rock site (NEHRP class). Source mechanism is unspecified.

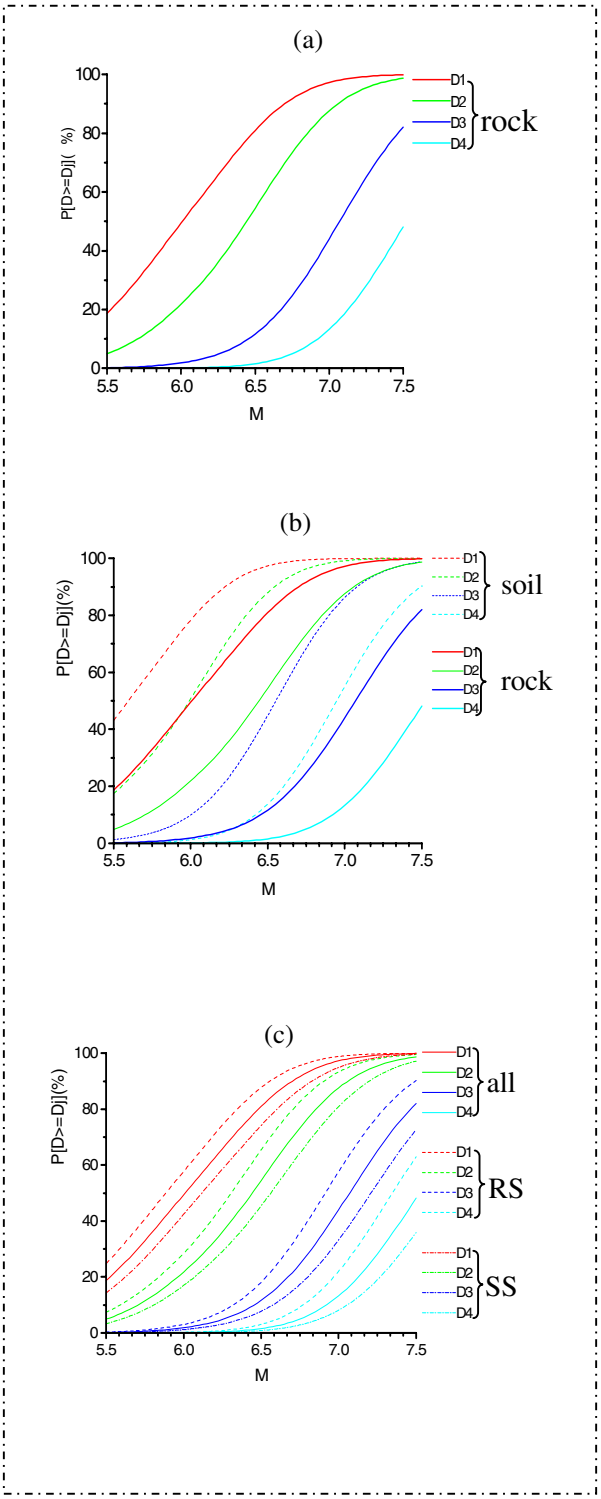

Fig.3 (a). Fragility curves on rock in terms of *M* at 15 km. (b) Effect of site condition on fragility curves. (c) Effect of source on fragility curves.

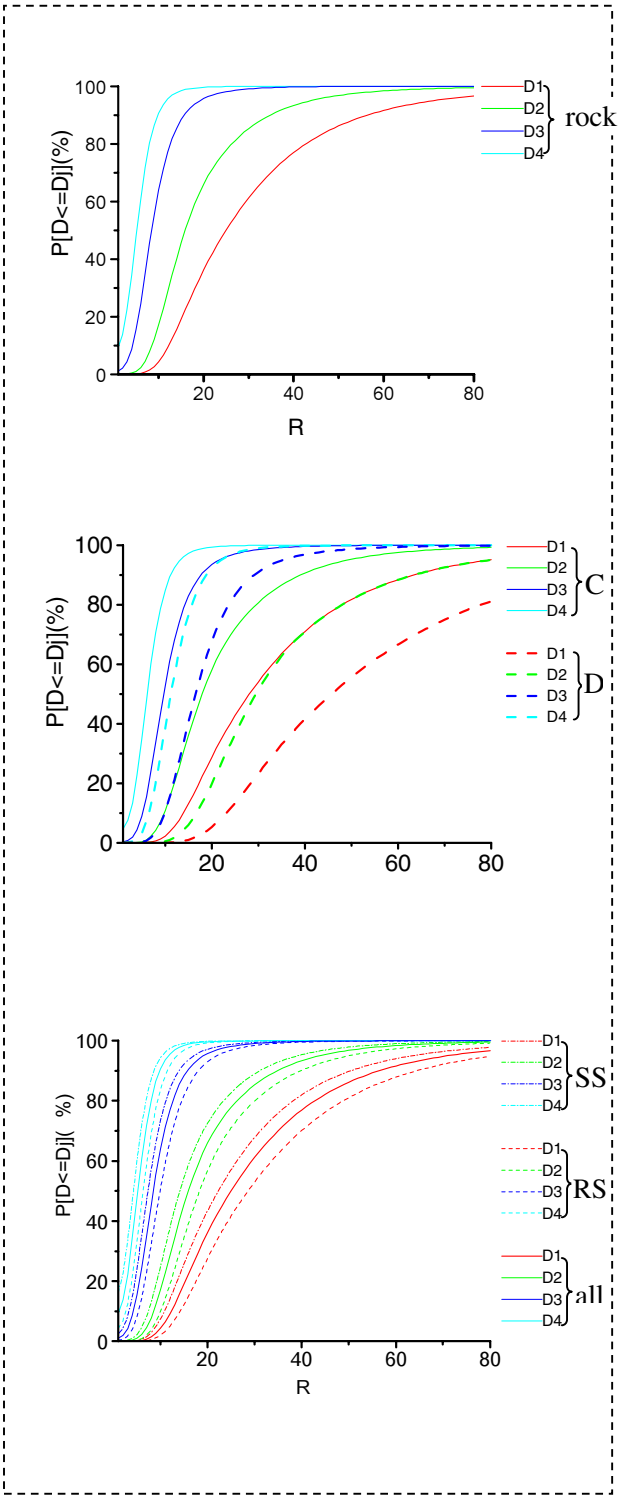

Fig.4 (a).Fragility curves on rock in terms of distance for magnitude 6.5: (b) Effect of site condition on fragility curves. (c) Effect of source on fragility curves

DISCUSSION AND CONCLUSION

Representation of damage probability distribution based upon MMI or PGA alone cannot yield any information of which source or site factor or which particular seismic sources contribute dominantly to the overall seismic risk of a building. A single parameter approach (either MMI or PGA) is not enough to characterize the destructiveness of an earthquake to a particular structure. It has been repeatedly demonstrated by many earthquakes that the seismic damage is highly selective, and the nearby earthquakes of moderate size make low-rise buildings experience heavy damage on a firm or rock site, whereas distant earthquakes of large magnitude cause damages in taller structures, particularly those on soft site. Thus, the single parameter approach can not characterize the seismic damage selectiveness.

In this paper, damage probability distribution surfaces are proposed and they represent the probability that a given structure's response to various seismic (conditions) excitations occurrences performance limit states. To consider damages in tall buildings, higher mode effects are incorporated through the use of modal superposition analysis. Magnitude is a size measure of an earthquake in terms of energy released at the epi-center. However, the destructiveness of an earthquake, although partly related to its magnitude, is also a function of many other parameters such as the distance from the epicenter, the soil conditions and mechanical properties of the structures. The advantage of the representation of damage probability surface is that the various combinations of source-path-site-structure effects can be taken into account simultaneously. The vulnerability assessment based on source-path-site system is an appropriate approach. More specifically, seismic hazard is first derived from the magnitude and distance disaggregation of probabilistic hazard analysis. The damage probability at any particular point from scenario the earthquake can then be used to evaluate damage attenuation characteristics. It offers the opportunity of damage spatial mapping in terms of probabilistic terms. It established damage probability distribution as a basis for using performance-based or consequence-based design, conducting a cost and loss assessment, and making sensible decision or policies. It is also used to develop optimal strategies for seismic rehabilitation based on cost-benefit analysis.

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