QUANTITATIVE SEISMIC HAZARD ASSESSMENT FOR SPATIALLY DISTRIBUTED SYSTEMS

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This paper discusses the global and aggregate response of infrastructural systems and large socio-economic complexes to a seismic environment. Emphasis is placed on the philosophy and usefulness of system global response parameters as seismic hazard measures. Aspects addressed include: what to measure, how to measure it, and what to do with the measurement.

INTRODUCTION

It is nowdays widespread practice in engineering to assess the likelihood of future potentially threatening phenomena at the site where a facility is located. Such information - even if imperfect - permits the more rational design of safety provisions against destruction and environmental damage. Moreover, though less frequently used, outage assessments and economic evaluations (e.g. downtime hazard and expected damage or losses) can be drawn from this same information. This latter class of assessments transcends from the traditional engineering field into the realm of planners, economists, system analysts and policy decision-makers. Yet, the devising of preventive policies, design and retrofitting criteria and disaster mitigation strategies, requires the implementation of techniques and models capable of quantitatively evaluating the impact of natural disasters or disturbances.

In approaching this problem, the analyst has to deal in most instances with systems, meaning by "system" a set of component facilities or resources that jointly perform a specific function or share a common attribute. An aqueduct is an example, as is a set of dwellings insured by an agency or company. Here, damage vulnerability or functional reliability acquires a new connotation since reliability of the system as a whole is an aspect different from the reliability of individual components. Thus, in dealing with "systems" the problem of <u>defining and quantifying global response</u> to threatening phenomena has to be recognized as a crucial aspect of forecasting their economic and social impact.

Much of the material in this paper is covered in more detail in a study by the author (Reference 1) which is part of the research on the subject currently being conducted at Stanford University.

GLOBAL RESPONSE MEASUREMENTS

Many analysis techniques make use of global response indicators as a means to characterize in a synthetic way the performance of an entire complex system. Gross national product is an example of a <u>global aggregate</u>

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parameter. Peak ground acceleration is intended to be a global representative measurement of an entire earthquake time history. Some global response indicators are even artificial from a strict physical point of view. The lateral drift of the top floor of a building, as predicted by an elastic structural analysis, has no real physical counterpart. Yet, it is used as a basis to characterize the flexibility of the structure as a whole.

In the same way, one can make use of this resource to approach the problem of quantitatively assessing the seismic performance of the systems addressed herein. It does not really matter how artificial a parameter may be as long as it can be successfully correlated to some "real world" situations of interest. It is perhaps more important that its evaluation is feasible from a technical and economical point of view. As a specific type of parameter becomes successfully quantifiable in practice, analysts gain experience in correlating it with the situations they want to analyze.

Global response parameters can be defined in a number of formats. The simplest one is of boolean character; either the system succeeds or fails in fulfilling some purpose. More powerful for many applications are multi-state descriptors. The difference between multi-state and continuous-state descriptors is conceptual; most analysis algorithms would require numerical analysis which yields multi-state results, yet as finely discretized as desired.

A number of global response parameters have been proposed in the earthquake engineering literature, though not always labeled the way they are in here. Path-existence (ref. 2) between two sets of nodes in a network belongs to the boolean group. Among those that can be considered multi-state or continuous-state parameters are: Network Impedance, the shortest traveling time, cost or length between 2 nodes of a network, as left after a seismic event; Network Flow-Capacity (reference 3), the maximum amount of flow that can be conveyed between 2 sets of nodes after the network has been damaged. The foregoing are representative measurements of the system response to damaging events. There are also some aggregate parameters to measure response: The number of non-operating components (reference 4) among the total number of (identical) system components is a multi-state descrete parameter; global-damage is a continuous-state measure of the aggregate damage incurred by a system after an earthquake (reference 1)

The previous list is not intended to be exhaustive. Moreover, it is clear that most parameters are not mutually exclusive but, rather, complementary in analyzing some system. From among them, global-damage will be discussed further in this paper to illustrate the points addressed in the next sections.

THE PROBLEM OF SPATIAL DISTRIBUTION

Many of the systems under consideration spread over large geographical spans. In assessing their seismic performance such spatial distribution with respect to the seismic environment has to be taken into account.

A geographically compact system may be assumed to be subjected to a more or less uniform earthquake ground motion severity* throughout its entire extension. All system components can then be supposed to be subjected to the same earthquake input which can be evaluated for a suitable, representative geographical site. A system analysis yielding the desired global response parameter can then be systematically conducted for varying levels of ground motion severity. Thus the probability of occurrence of a certain response level is that of the corresponding seismic input which can be assessed by means of any of the well-known site-oriented seismic hazard analysis methodologies.

On the other hand, in many systems few or none of the possible seismic events are capable of damaging the entire system. At least not with a uniform severity. In these cases the assessment of the probability of occurrence of a given set of damage circumstances has necessarily to consider the extension of the felt areas of earthquakes and the distribution of seismic severity within them. Obviously, in most cases, the number of possible "earthquake severity patterns" within an extensive area is overwhelmingly large. Hence, the recurrence of given sets of circumstances is extremely infrequent. This introduces two problems: difficulty in typifying earthquake severity patterns and inability of properly calculating their probability of occurrence because of their sparseness.

However, what one really needs is to assess the probability of occurrence of various levels of the global response parameter. It is much more likely that many disparate damaging events happen to yield the same level of response. Therefore, it is more convenient, in this type of analysis, to waive the description of seismic hazard in terms of earthquake ground motion severity parameters and obtain it directly in terms of the magnitude of the system-damage parameter.

Clearly, this requires an analysis technique that, given the characteristics of seismic events at their source, models ground motion severity at the sites of interest; evaluates damage incurred by the components; analyzes the response of the system as a whole and then, keeps track of the levels of response. All in a single algorithm. Such type of algorithm has been researched. Some are closed form solutions carried out by numerical integration (as in references 3, 4). Others are based on computer simulation techniques (reference 1).

The discussion that follows assumes that such algorithms are either available or that their implementation is feasible.

SEISMIC HAZARD IN TERMS OF GLOBAL RESPONSE

So far, we have seen that for a system seismic analysis, it is convenient to describe earthquake hazard directly in terms of global response. The question to be addressed now is how to represent such information in adequate terms to undertake a subsequent risk analysis.

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* The term "ground motion severity" encompasses herein such measures as peak ground acceleration, ground velocity, Mercalli intensity scale, strong motion duration, etc.

The simplest and less comprehensive approach is to select an earthquake of given magnitude and location. For this event the seismic performance analysis, as described in the previous section, is conducted. The result is a point estimate of the magnitude of the response parameter. If the analyst has a probabilistic statement about the likelihood of the seismic event, then the obtained response level has the same probability of occurrence.

An improvement of the previous approach is the consideration of a reduced number (heuristically manageable) of possible events (described by their seismic magnitude and location) whose probability of occurrence has already been assessed. As a result of the system seismic performance analysis, a set of system response magnitudes is obtained, the probability of each inferred by elementary probabilistic analysis.

The obvious generalization of the foregoing method is to subject the system to "all" possible seismic events ("all" possible seismic magnitudes at "each" possible location), for which the probability of occurrence or, else, the mean interarrival time is known. The probability of occurrence of system response magnitudes, r, within prespecified intervals (R_k, R_{k+1}) is then numerically integrated while performing the system analysis. The final result - the seismic hazard assessment - would then be a statement about the probability of, say, zero occurrences, in time t, for each interval, i.e.,

$$P(n = 0 | t, r_k < r < R_{k+1}) = p_k; \; k = 0, 1, \ldots, m$$

which can be alternatively expressed in terms of Return Period (mean interarrival time). The results above are, generally, more conveniently expressed in cumulative form. Finally, the foregoing probabilistic statements can be projected to time spans different from that for which the results were computed (usually one year). This is done by assuming they respond to a stochastic process, usually an elementary one such as the Bernoulli process.

Sometimes complete systematical enumeration of "all" possible seismic events demands an overwhelming modeling and computational effort. This is especially true when the modeling relationships (e.g., seismic attenuation and performance of components) and/or the input data (seismic recurrence) are assumed to be uncertain. It is also possible that the analyst requires an estimate of interarrival time distributions rather than just point estimates of probabilities of occurrence or mean interarrival times. In these cases one can resort to computer simulation as an alternative to the enumerative approach. For this, one models the earthquake generating mechanism as a stochastic process rather than just taking the average recurrence of seismic events. By generating random numbers one allows the process to generate earthquakes of its own, for which the system response is evaluated. By collecting the statistics of the randomly generated responses one can obtain the same kind of results described in the previous paragraph by means of statistical inference. Moreover, one can readily obtain interarrival time distributions or simulated time-histories of the occurrence of damaging events. Nonetheless, simulation in return of being more flexible and approachable yields uncertain results as any other statistical experiment. That is, it introduces additional uncertainty on the results besides that inherent to the input data. This additional uncertainty is, however, controllable to a certain extent. Bearing the previous warnings in mind, and in summary, the analyst puts himself one step ahead in describing explicitly the global response of the system in terms of a stochastic process.

In the exposition that follows, it is assumed that the global or aggregate response of systems to seismic events can be described by means of a compound stochastic process. The process evolves in two states: time and magnitude of the system response.

GLOBAL-DAMAGE AS A MEASURE OF SYSTEM PERFORMANCE

To illustrate the previously outlined subject, a very versatile parameter will be discussed. Global-damage is an aggregate measure of the damage incurred by a system during a seismic event. In simplistic terms, it is tantamount to evaluting the bill that has to be paid after an earthquake has shaken the system by adding the damage incurred by the individual system components. Symbolically, global-damage due to a seismic event $\underline{X}$ (where $\underline{X}$ is given by the magnitude and location of the event) can be expressed as

$$G_{\underline{X}} = \sum_{i=1}^{nc} m_i d_{i\underline{X}} \qquad (1)$$

in which nc is the number of system components; m_i is the "mass" of component i (some measure of its size) and $d_{i\underline{X}}$ is a measure of the level of damage incurred by the unit of mass of component i, due to the event $\underline{X}$.

The components throughout the system do not need to have a homogeneous unit of mass as long as the product m*d does. The reason for defining a mass is that the concept of typical components, with typical responses per unit, can be used. The components, as seismic targets are assigned point geographical locations. If a component is spatially distributed, such as a pipeline, then it can be divided in sectors, each one of which can be assigned a representative point location.

The evaluation of damage per unit of mass is a key consideration in the analysis. It can be carried out by means of Seismic Performance Relationships. Such relationships are probabilistic or deterministic mapping functions that directly correlate earthquake ground motion severity to a measure of damage (monetary value, percent of destruction, lives lost, etc.). The relationships can be set up by either of the following techniques: by analytical modeling of the response; by statistical analysis of historical data or by subjective expert "guess". Performance relationships are discussed in more detail in reference 1.

The system, modeled as a set of spatially distributed point seismic targets can now be subjected to the analysis as previously described. As a result, the system response stochastic process in terms of global-damage is obtained.

In a number of circumstances, which are discussed in reference 1, the response process can be assumed to be compound Poisson. If such is the case, the results are of the form

$$\left.\begin{aligned} P(n|t,G) &= (t/RP)^n \exp(-t/RP)/n! \\ RP &= \psi(G) \end{aligned}\right\} \qquad (2)$$

in which $P(n|t,G)$ is the probability of n occurrences, in time t, of system global damage (larger than) G. RP is the return period of global-damage (larger than) level G. The function $\psi(\ )$, more conveniently expressed in cumulative terms, is generally represented in tabular or graphical form (as in Figure 3) and constitutes the core of the analysis results. Equation 2 altogether, is the seismic hazard evaluation. To assess seismic risk economic or social considerations have to be taken into account as illustrated in the next section.

APPLICATION EXAMPLE

A system has been discretized into 38 components located in pairs at 19 sites which span over several hundreds of kilometers, as shown in Figure 1. The system could be, for instance, the major facilities of an aqueduct for which the aggregate amount of damage incurred as a consequence of earthquakes is to be assessed. In the example, only two types of facilities, A and B, located in pairs at each site, are considered. For simplicity, all facilities type A were assigned a mass of 5.0 and all B, a mass of 2.0. The corresponding Performance Relationships are depicted in Figure 2. The input ground motion parameters for the relationships are peak ground acceleration and duration of strong motion, for each combination of which, a deterministic response is given in terms of damage ratio of the unit of mass. The damage units are not specified for this example since this would not be relevant to the discussion. The reader may assume they represent monetary value, size of repairing teams or any other such quantity.

A system analysis whose details are out of the scope of this paper, but whose method has already been sketched, yielded a process of Poisson characteristics with a response function $RP = \psi(G)$ as shown in Figure 3. The function is cumulative giving the return period of events larger than the argument. As a parenthetical comment, it is convenient to keep track during the analysis of the response of individual components. This will enable the analyst to detect the weak and strong spots of the system, a subject not addressed herein.

Some simple examples of the use of the results in conducting a risk analysis are given next:

1. Consider that the damage units represent monetary value, \$1.00 per unit. Expected losses per year can be obtained by numerical integration

over the entire state-space of G, of the average losses in an interval (G_{i-1}, G_i) times the expected number of yearly occurrences in the interval which, since the curve is cumulative, is given by the difference between the reciprocals of the return periods at i-1 and i. For the curve in Figure 3, this yields approximately \$1.40/year. The present value of the accumulated losses over a 30 year period given an interest rate of 0.05 would be

$$E(Loss|t = 30,\ r = 0.05) = 1.40*30/(1.05)^{30} = \$9.72$$

2. Consider each damage unit be a life lost. Then, Figure 3 indicates a maximum forseeable death toll per event of about 70 (see curve upperbound). The expected accumulated death toll over a 30 year period, with expected deaths per year as computed above, would be

$$E(deaths|t = 30\ years) = 1.40*30 = 42$$

3. Let the damage units be worth again \$1.00. Suppose that presently the maximum insurance coverage per seismic event is \$40 for the entire system. Consider that any out-of-pocket contingent spending of more than \$10 is very severe for the system owner. The probability of reaching at least once in 30 years this critical situation would be

$$1.0 - P(n=0|G > 50,\ t = 30) = 1.0 - \exp(-\ t/RP_{50})$$
$$= 1 - \exp(-\ 30/1130) = 0.026$$

CONCLUDING REMARKS

It is natural to raise the question of how valid the quantitative results of analyses such as those described in this paper would be. The uncertainties involved are certainly overwhelming. One cannot really expect a high confidence level given the state of information on seismic recurrence and on seismic performance for many types of facilities. This in addition to state-of-the-art limitations in the analysis models.

However, skeptical as one could be about the cardinal values of the numerical results, their reliability as weighting factors is far larger. Then, their worthiness as ordinal values, as in comparing alternatives, is hardly debatable. Most professional decision-makers would agree that accuracy of cardinal values is frequently secondary in deciding among less than a handful of feasible alternatives.

Moreover, one should be optimistic, recalling that improvement of techniques is associated with the experience gained in making use of them.

ACKNOWLEDGMENTS

The sponsorship of the U.S. National Foundation by contract ENV-77-17834 is deeply appreciated. This research is being conducted by the author in the John A. Blume Earthquake Engineering Center, Dept. of Civil Engineering, Stanford University, under the supervision of Professor Haresh C. Shah

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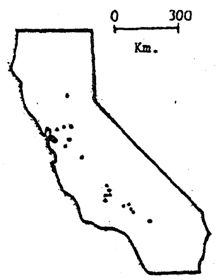
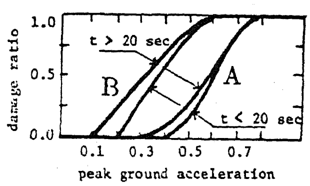
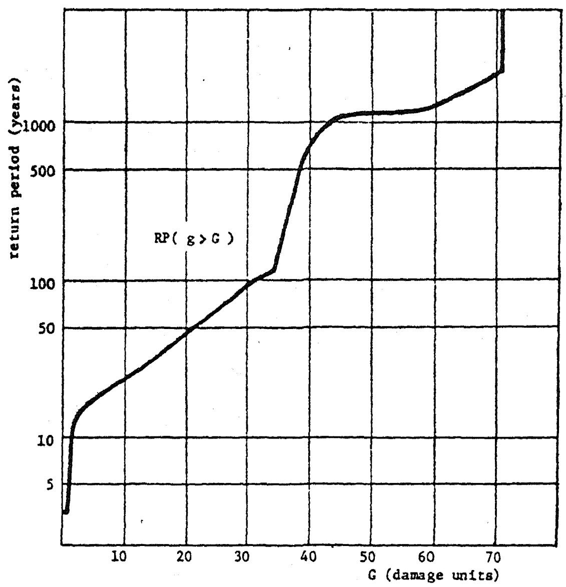


SYSTEM GEOGRAPHICAL LAYOUT
FIGURE 1



PERFORMANCE RELATIONSHIPS
FIGURE 2



GLOBAL-DAMAGE CUMULATIVE GRAPH
FIGURE 3