Liu 1/8

11 WCEE

***Paper No. 1910. (quote when citing this article)***
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

# SEISMIC OPERATIONAL RISK ANALYSIS

Mukund Srinivasan, Xudong Liu and Gordon Park

Hart Consultant Group, 2425 Olympic Blvd, Suite 670
Santa Monica, CA 90404-4034

University of Southern California
Los Angeles, CA 90089

## ABSTRACT

This paper presents a methodology for the Seismic Operational Risk Analysis (SORA) of a building or group of buildings which are part of a large facility such as a hospital group wherein the continued operation of the building after an earthquake is a critical design objective. SORA's performance based seismic risk approach has the advantages of allowing planners to prioritize limited financial resources, identify seismic vulnerabilities and be part of a complete econometric model for effectively delivering healthcare through seismic events.

## KEYWORDS

Seismic Risk; operational analysis; healthcare; SORA; performance based analysis; multi-disciplinary model

## INTRODUCTION

This paper presents a methodology for the seismic operational risk analysis of a building or a group of buildings from the perspective of the continued operation of the building(s) after an earthquake being a critical design objective. As a general model, it is benchmarked against multiple site data from the January 17, 1994 Northridge, California 6.8 Magnitude earthquake. This allows it to bring a degree of realism to estimates of damage and down time for critical facilities - subjective factors which otherwise cannot be estimated with any degree of accuracy.

The SORA model can be used to pinpoint the weak links in the existing building or systems as well as identify management and operational vulnerabilities in facilities providing essential community services especially in times of seismic disasters. The SORA model considers many variables and their separate and combined influence on the system performance. By itself, it provides a skeletal structure to a complete risk analysis methodology and can be used on other large facilities such as universities and school systems in addition to its presently described use in healthcare facilities. The SORA model assumes that the loss of function of a hospital is dependent upon the level of the earthquake and the weakest system - structural, mechanical or electrical. It can be seen in the example in Figure 1 that failure of the hospital occurs from a failure in the mechanical and electrical systems.

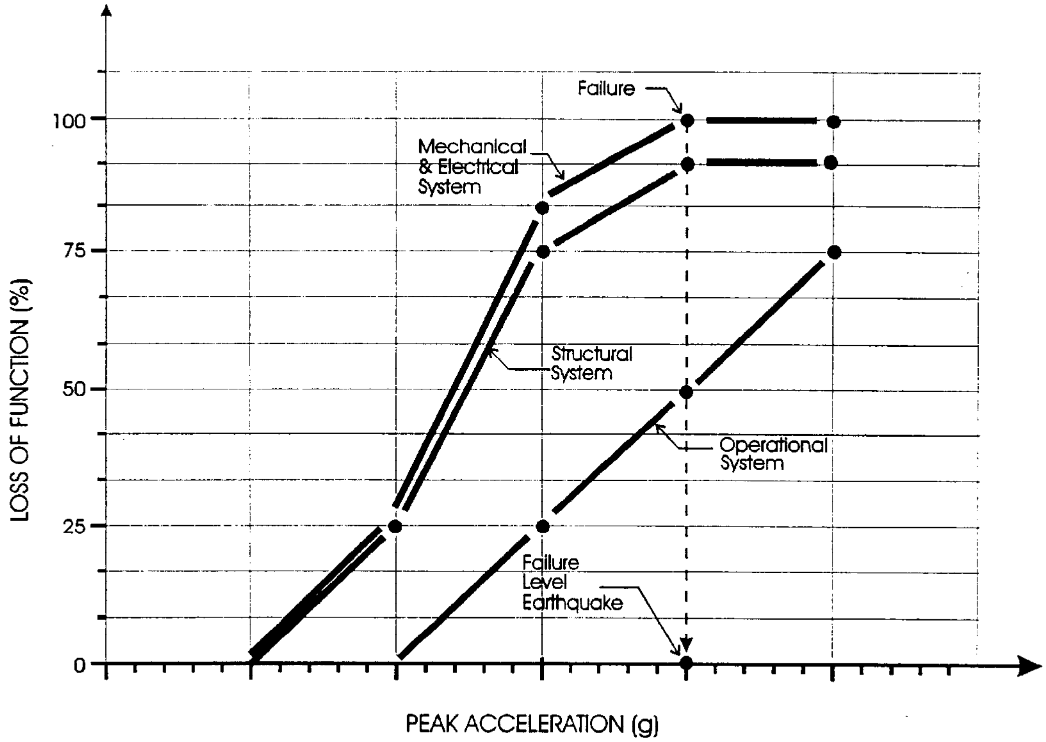

FIG. 1 PERFORMANCE BASED SEISMIC RISK APPROACH

The SORA model has been applied to a healthcare organization as a disaster preparedness strategy. It can be used by any managed system to prioritize the expenditure of limited financial resources while optimizing the ability to fulfill their business objectives. The final product of the model is a series of recommendations with the highest - priority 1 seeking to maximize hazard reduction at the lowest level of cost. It also identifies the "weak links" in the chain allowing the organization to respond at low cost levels. Other alternative management plans can also be used in place of these recommendations.

## ANALYSIS METHODOLOGY

The proposed SORA model is based upon a matrix approach to the issues of building design, structural design, mechanical, electrical, plumbing, telephone, systems and operational considerations that affect the workings of the hospital or institution. As such, the project team must include architects or architecturally trained operations managers, structural and earthquake engineers, mechanical and electrical engineers, and geotechnical engineers.

The SORA model starts by identifying and dividing the entire building(s) into zones in the zone identification study phase of the project. Following the zoning of the building, each of the project groups - structural, mechanical and geotechnical proceeds to perform their individual analyses prior to a meeting where all the results are presented together to assign values of damage called risk evaluation factors.

### Zone Identification Study

This phase of the proposed methodology is one of the most important links in piecing together the dynamics of the hospital's operation. Hence considerable interplay between the project team, the owner's architect and the hospital operations staff is essential. Any large facility in order to be studied, has to be divided into a manageable number of building areas or zones for the operation to be studied in fine enough detail.

A structural zone in a building is defined to be an area of a building floor that has a unique motion from other areas in the building due to a seismic event. Modern building complexes typically consist of one or more buildings connected together with bridges or covered over seismic joints. For example, the corners of the floors tend to move more than the center of the floors due to the twisting motion of the floor in irregularly shaped buildings.

The MEP (mechanical, electrical and plumbing) zone is different from a structural zone because mechanical equipment tends to be clustered at a single distribution point. The Identification of MEP zones typically is easier to identify through structural zones that depend on the motion of the building. The MEP zones are established by the MEP engineers using mechanical/electrical and plumbing drawings of the hospital. An MEP zone can span over two floors but can also be different on a given floor in adjacent floor areas.

An operational zone of the hospital is defined in terms of the task that is performed in the zone in the context of the hospital's operations. Examples of operational zones are Surgery, Pharmacy and Intensive Care Units. For convenience, sometimes it is possible to group operational zones together when one of the zones does not perform a critical and irreplaceable task. For example, office space can usually be grouped together regardless of their specific uses.

Once each group of experts independently completes their individual zoning, the zones are shrunk to common building zones, each with unique structural, building, mechanical/plumbing, electrical and operational characteristics.

## Site Seismicity Analysis

The Northridge Earthquake presented a unique learning experience and also provided critical information in terms of actual damage. This provided the project team with a benchmark used in estimating the expected damage for future seismic events. Ground shaking information at the hospital may therefore be available. In this case study it is assumed that ground shaking information is available and the ground motion at the hospital site from the 6.8 magnitude Northridge Earthquake, 20 miles away, was estimated as having a peak acceleration of 0.24g or 24 percent of gravity. For convenience, the earthquake ground shaking was defined in terms of ground shaking scenarios. Scenario 1.0 was defined as a peak acceleration of 0.24g. Further scenarios were developed in increments of 0.25g i.e. 1.25, 1.50, 1.75 up to a maximum ground shaking scenario of 3.00, where the scenario numbers indicate the multiple of the peak acceleration of 0.24g.

The ground motion at hospital site is now defined in terms of scenarios. Also, the peak acceleration that is associated with a scenario has an assigned probability of occurrence that may be estimated in a finite time span. Therefore, the scenario provides a means of clearly communicating results between the earthquake engineer and the owner and other non-engineers. A specific scenario ground motion may occur at a site due to any number of earthquakes occurring in different locations and different magnitudes.

After the peak ground acceleration experienced by the hospital is estimated, a Probabilistic Seismic Hazard Analysis (PSHA) must be performed for a wide range of ground motion recurrences. The probabilities of a ground motion scenario being exceeded were obtained for exposure periods of 7, 14 and 21 years. Table 1 shows an example of such seismic risk information. Probabilistic response spectra are generated for use in computations of building response for the various scenarios, with one spectrum for each scenario of ground motion.

Table 1 Seismic Risk at Hospital

| SCENARIO | P.G.A (g) | MAGNITUDE LOCAL EVENT | PROBABILITY OF EXCEEDANCE (%) | | |
|---|---|---|---|---|---|
| | | | 7 YEARS | 14 YEARS | 21 YEARS |
| 1.00 | 0.24 | 5.0 | 18 | 33 | 44 |
| 1.25 | 0.30 | 5.4 | 8.4 | 16.0 | 22.0 |
| 1.50 | 0.36 | 5.6 | 3.8 | 7.0 | 11.0 |
| 1.75 | 0.42 | 5.8 | 2.0 | 3.9 | 6.0 |
| 2.00 | 0.48 | 6.0 | 1.5 | 2.9 | 4.2 |
| 2.25 | 0.54 | 6.1 | 1.2 | 2.3 | 3.3 |
| 2.50 | 0.60 | 6.2 | 0.9 | 1.8 | 2.6 |
| 2.75 | 0.66 | 6.4 | 0.5 | 1.1 | 1.5 |
| 3.00 | 0.72 | 6.6 | 0.3 | 0.6 | 0.9 |

## Structural Analysis

One of the crucial links in analyzing the damage to the hospital is the accurate quantification of structural performance for each of the structures to be studied. It is important that an analytical basis be used for determining structural performance and also that the method chosen should include the non-linear or post-yield behavior of the structure. This is particularly important in view of the fact that in a moderate to severe earthquake, many older buildings experience yielding of their structural elements. The capacity of a building ( from a life-safety perspective ) can be significantly underrated if only elastic behavior is used.

Two different types of structural behavior should be explored. The first type of analysis is called a Behavior State Analysis (Some people call this a "Push Test" analysis). The structure is subjected to increasing static loads until it yields and moves into the nonlinear range. The resulting deflections are plotted, and an example of this is shown in Figure 2. The second type of analysis is the "Time-History" analysis that is currently being used for the design of special structures such as base-isolated buildings. Earthquake records obtained from the geotechnical engineers are used in the computer model to predict structural behavior. Peak values of building performance such as floor displacements and drifts ( inter-floor displacements ) are then obtained for the time history. Both analyses are used to evaluate the expected response of the building in the S.O.R.A study.

## MEP Analysis

A MEP analysis must be performed in conjunction with the structural engineering experts. In order to accomplish this task, the experts used maps of the MEP diagrams and other external sources involved in the project to study the response of the various mechanical/electrical components to ground motion or building motion. In conjunction with the results from the structural analysis, the MEP engineers determined the response of the various components and evaluated their integrity at various levels of ground motion. Values of earthquake induced displacement and drift (interstory displacement) were provided by the structural engineers for each ground motion scenario so that the resulting disruption to MEP services could be evaluated. Field investigations in conjunction with a special emphasis on equipment deemed vital to the decision making process were also conducted. This phase of the analysis was also utilized in the zone analysis of the hospitals. The MEP analysis also included the checking of weak links that could cause the hospital to close because of insufficient resources (gases, air-conditioning or possible flooding).

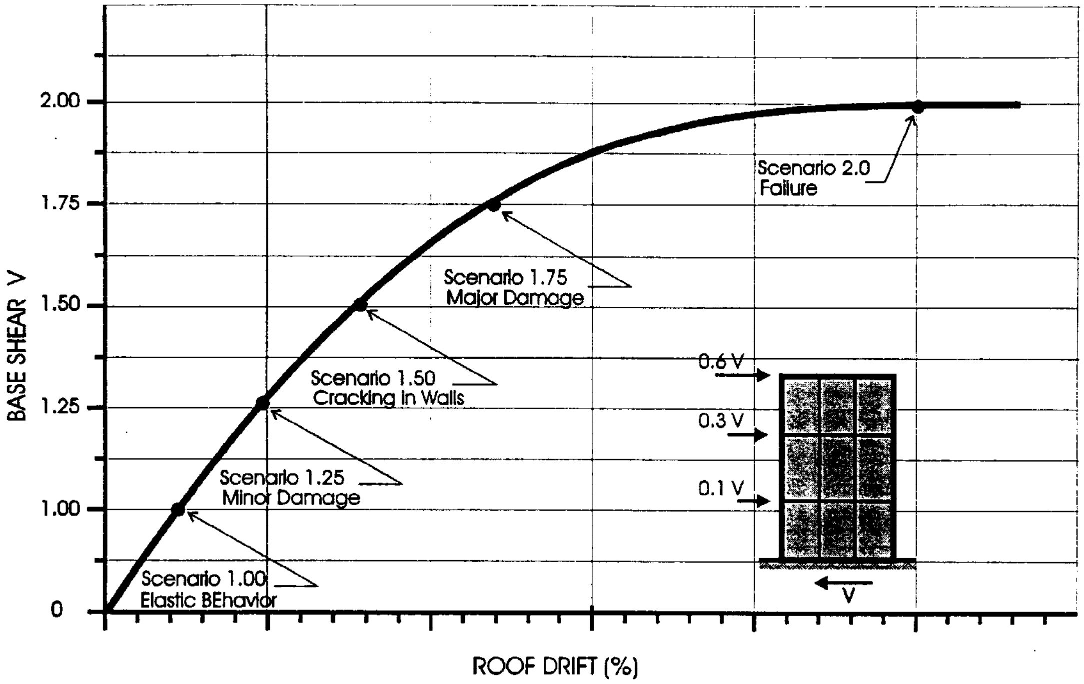

**FIG. 2 BEHAVIOR STATE ANALYSIS**

## DISRUPTION SCENARIO ANALYSIS

For each scenario, the entire project team collectively assigned values to an "evaluation factor" for six aspects of the hospital performance identified as Building, Structure, Operational, Mechanical, Electrical and Matrix. This was done on a zone by zone basis. These terms are defined as follows:

| | |
|---|---|
| BUILDING | Quantifies the level of damage related to the location of that zone. Is one area more likely to fail than the other due to its location or age or code changes ? |
| STRUCTURE | Quantifies the level of structural damage due to the particular structural characteristics of that zone. |
| OPERATIONS | Quantifies the extent to which hospital operations are curtailed. |
| MECHANICAL | Quantifies the extent to which mechanical and plumbing systems are damaged in that zone. |
| ELECTRICAL | Quantifies the extent of damage to electrical systems in the zone. |
| MATRIX | This item is used to define the extent to which hospital operations are affected by damage in this zone. It thus identifies those areas critical not just to themselves but to a wider area of services. |

The analysis is performed by using the results of the Structural and MEP analyses previously described. The operational analysis was performed by using the judgment of the hospital operational personnel in conjunction with verbal descriptions of motion and damage as related by the structural and MEP experts.

hospital under increasing seismic events can now be obtained. Areas with large evaluation factor sums indicate critical points. Areas with low values indicate little or no damage or effect to continued operations. This evaluation was repeated for each scenario until a complete shutdown of hospital operations is identified. Table 2 shows a disruption matrix table for the Hospital showing the state of the hospital operations at a given earthquake scenario.

Table 2 RISK EVALUATION FACTORS
SCENARIO = 2.0 ( 0.48 g)

| ZONE | COMPONENT | BLDG | FLOOR | BLDG/STRUC (max = 5). | MEP (max=10) | OPS (max=5) | MATRIX (max=10) | TOTAL (max=35) |
|---|---|---|---|---|---|---|---|---|
| 1 | Emergency | A | 1 | 3 | 3 | 3 | 2 | 11 |
| 2 | Elevators | A | 1,2 | 3 | 4 | 3 | 10 | 20 |
| 3 | Surgery | B | 2 | 2 | 3 | 3 | 2 | 10 |

The total risk evaluation factor for a given zone can be converted to the number of days down by the project team and provides a link between the theory of SORA and its practical implications for the facility.

## Macro Operational Unit

While a zone by zone analysis is necessary to evaluate seismic risk, it presents the micro picture of the performance. Owners and corporate officers who want to know how the hospital will perform in a more global sense usually need to see an amalgamation of the micro picture. Hence the methodology proposes the use of a Macro Operational Unit ( MOU ). A macro operational unit is a collection of zones performing similar functions with possibly different behavior to seismic events. The macro operational units for the hospital are created by, or with the help of, the Architect and represent a compilation of major hospital functions. Macro operational units can therefore be compared from hospital to hospital for seismic behavior if one ownership operates multiple hospitals. An example of MOU's are shown in Table 3.

Table 3 MACRO OPERATIONAL UNITS

| MOU | DESCRIPTION | COMPONENT BUILDING ZONES |
|---|---|---|
| 1 | Medical Surgery Beds | 1,3 |
| 2 | Elevators, Central Plant | 2,4 |
| 3 | ICU, CCU, NCU | 5,6,7 |

## Monte Carlo Time Line Analysis Simulation

The determination of the risk and the potential life cycle impact on the hospital is essential input to a decision on how to seismically rehabilitate the hospital in part or in total. A time line analysis is an analysis intended to provide information in this regard and the duration of the time line is the life cycle. The time line analysis simulates a very large number of possible scenarios (based on the site seismic risk information) on a year by year basis for the duration of the life cycle. Therefore, if we were looking at earthquakes over a life cycle of 21 years, we would have to simulate the level of the earthquake for each year ( assuming that multiple events in a single year are not considered ) for a total of twenty one events. This is one possible scenario that may occur over the next 21 years. Each simulated earthquake is then converted to a scenario and then to a number of days down for the zone and statistics of these quantities can be found. A sample of the simulation timelines of earthquake scenario and days down is shown in Figure 3. However, what is of more interest to the manager is the probability of exceeding specified levels of damage or days down to the hospital. For example, the question to be answered could be " What is the probability of exceeding a total of 30 days down for the Elevators over the next 7 years ?". The answer to this question is obtained from the union of the site specific seismic risk and

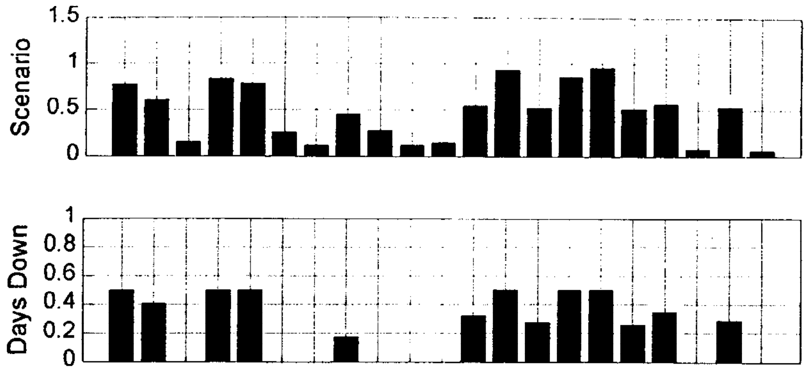

Fig. 3 Simulation Timelines of Scenario and Days Down

the hospital's specific disruption scenario matrices. This is performed by combining the seismic risk to the site (in terms of the site specific response spectra) and the building vulnerability (in terms of the risk evaluation factor tables for each MOU) to yield an estimate of the days down expected over timelines of 7, 14 and 21 years. This is shown in Table 4 for a 21 year period.

Table 4 PROBABILITY OF EXCEEDANCE FOR DAYS DOWN
(21 Year Timeline)

| M.O.U | Number of Days Down | | | |
|---|---|---|---|---|
| | 1 day | 1 week | 6 months | 1 year |
| 1 | 44% | 18% | 17% | 15% |
| 2 | 37% | 18% | 16% | 14% |

This table therefore is the combination of the seismic vulnerability and the seismic risk and presents the true picture of the events expected at the hospital over the immediate future. It also allows for comparison of loss of essential functions over several hospitals owned or operated through the use of the Macro Operational Unit concept. Further, it allows for the manager to identify hospitals with significant combinations of vulnerability and risk to enable resource prioritization. The singular advantage with using such a table is that the consequences of taking no action for a period of 7, 14 or 21 years can be understood in terms of the relative risks. Planning that is based even partially on random events such as earthquakes is subject to inherent variability and therefore acceptable levels of risk for various possibilities are used to make decisions.

The SORA study is essentially complete at this point. The results of the study are a comprehensive set of risk evaluation factor tables for the entire hospital for each scenario of earthquake motion. In addition, a set of probability of exceedance tables for each of the MOU's for timelines of 7, 14 and 21 years are also available. An additional advantage that arises out of the SORA exercise is a greater awareness of hospital functions and vulnerability to the participating management of the hospital that may not be easily communicated in reports typically written by outside consultants with little hospital staff participation.

## PROJECT RECOMMENDATIONS

The primary objective of the SORA project is to provide a disaster preparedness document that could be used to identify weaknesses in the organization's ability to provide healthcare through seismic events, aid in the prioritizing of resources within a given hospital as well as aid in the prioritizing of resources over several hospitals. In addition to these issues, upgrade recommendations concerning the actual structural and MEP systems were also made and split into three groups or priorities.

Priority 1 recommendations are those that can improve and extend the operational life of the hospital in a seismic event for a relatively low level of cost. Examples of such recommendations could be strengthening for a specific column or a protective roofing for an MEP installation etc.

Priority 2 recommendations are similar to Priority 1 recommendations but need to be carried out over a longer time span and are more disruptive. These typically involve local element strengthening.

Priority 3 recommendations are of a substantive nature and involve long term implications to the continuing operation of the hospital and an example of such a recommendation would be the structural upgrade of the entire hospital to current code.

At the conclusion of the SORA analysis, the hospital management has obtained a detailed operational working plan of their hospital through a seismic event, information on the performance of specific hospital operations, weak links that may make the hospital vulnerable to seismic events as well as answers to long term planning questions. Therefore it provides a complete risk analysis methodology for use by planners for not only hospitals but also institutions of a similar nature.

## REFERENCES

Papoulis, A (1984). Probability, Random Variables and Stochastic Processes . Mc Graw-Hill, New York

Park G.N., Hart G.C, Srinivasan M., Johnston R., Lew M., Hudson M. and Popov R. (1995). Seismic Operational Risk Analysis S.O.R.A - Multidisciplinary Project Task Paper, Hart Consultant Group, Santa Monica, CA

Processed CSMIP Strong Motion Records from the Northridge, California Earthquake of January 1994: Reports 94-07,94-08,94-09,94-10 (1994). California Department of Mines and Geology, Sacramento, California.