APPLICATION OF THE SEISMIC RISK EVALUATION FOCUSING ON THE SAFETY OF EMPLOYEES IN INDUSTRIAL BUILDINGS

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ABSTRACT**:** In order to evaluate seismic risk of industrials, it is necessary to consider not only the physical and economical damage but also casualties from the viewpoint of Business Continuity (BC) and Corporate Social Responsibility (CSR). For a single building, one of the authors, Takahashi et al. (2002, 2004), proposed a seismic risk management methodology, and demonstrated that the life-cycle cost is useful to explain a reduction/increment of physical and economical damage. In this paper, the methodology is extended to the seismic risk management of multiple buildings. As a case study, we deal with multiple industrial buildings, owned and operated by a single company. These building are assumed to be located near the ten major harbors in Japan. In dealing with an industrial building that accommodates many employees, it is significant to consider their safety. Thus this paper focuses on the computation of the probabilities that the building incurs severe damage states, as the primary indexes of employees' safety. The estimated damage probabilities of the buildings will assist the manager of the company to decide on the priority of seismic upgrade of the existing buildings upon its limited budget.

KEYWORDS: seismic risk management, multiple buildings, earthquake probability, damage probability

1. INTRODUCTION

The Mid Niigata Earthquake, on October 23, 2004, revealed that the distinctive negative effects of seismic events on industrial facilities are startlingly apparent. One of the largest electric plants in Ojiya city was closed about two months because of physical damage of facilities and disruption of lifeline-utility system. They reported that the earthquake damaged up to 50 billion yen including repair and replacement costs of facilities and business inventories losses. Consequently, it caused serious impacts on the business continuity of the company. Another example, an automobile component plant could not resume its speedometer assembly line, which caused its senior motor company to halt automobile production at four plants elsewhere in Japan. There were many other plants shut down for more than one week, and then the total economic impact was estimated to be approximately 300 billion yen only for the commercial and industrial business. Fortunately, the Mid Niigata Earthquake happened in Sunday evening, and there were no casualties in the industrial facilities. However, it is necessary to mitigate not only the physical and economical damage but also casualties from the viewpoint of Business Continuity (BC) and Corporate Social Responsibility (CSR).

The Headquarters for Earthquake Research Promotion (HERP) organized by the Japanese government has been announcing the probability of large earthquake that are expected to occur around Japan. Among them, some were forecasted to occur in very high probabilities within the next 30 years, e.g., 99% for Miyagi-ken-oki earthquake (M_w=7.5), 50% for Tonankai earth- quake (M_w=8.1) and 40% for Nankai earthquake (M_w=8.4). Near such seismic sources, a manager of a company should prepare for the possibly imminent earthquake in the design of a new building or upgrade of an existing one. However, the manager should be based upon limited budget, and thus they would be reluctant to invest in future events. Structural researchers and engineers have been developing “hard” seismic technologies, for example, strong and ductile frames, bearing walls, energy dissipation dampers, base isolation systems and so on. On the other hand, “soft” technology to persuade the manager of company to invest in such sophisticated “hard” technology is not sufficiently developed. This causes the barrier to the efficient spread of safer buildings in our society.

1.1 Background

Under these situations, Takahashi et al. (2002, 2004) proposed a seismic risk management methodology aiming to persuade building owners to invest in appropriate seismic systems. Here, seismic risk management is defined as a decision problem among multiple design alternatives. Alternatives for seismic design or upgrade may be an existing frame designed according to a design code, with strong and ductile frames, with bearing walls, with energy dissipation systems, with base isolation systems, purchasing earthquake insurances, or a combination of any of these. The alternative that minimizes the total expenditure, i.e., the life-cycle cost, to the building owner including the initial cost and the cumulative damage cost due to all earthquakes that occur during the lifetime of the building, is chosen as the optimum selection. The expected life-cycle cost of each alternative is formulated so that we can directly introduce earthquake probabilities in the surrounding seismic sources, which have been constructed by HERP or WGCEP (1999). In addition, for computation of the expected damage cost due to earthquakes of a given magnitude, we can utilize up-to-date simulation techniques developed in the relevant fields such as seismology, geotechnical engineering, structural engineering, and social economics.

The proposed methodology was applied to various single buildings, such as office, hospital, city hall, detached house and so on (Working Group on Seismic Risk Management (WGSRM), 2005). Especially to the single industrial building, Murach et al. (2005) also applied the methodology, and demonstrated that a passive energy dissipation system using the oil dampers is effective in reducing the life-cycle cost.

1.2 Objective

For multiple buildings owned by a government, a local authority, a private company or of course an industrial, it is more important to apply the risk management methodology to persuade the owner or manager of an entity in seismically active regions to adopt appropriate investments. In the previous studies, it is demonstrated that the life-cycle cost is useful to explain a reduction/ increment of physical and economical damage. However, dealing with issues related to the industrials, it is also significant to take into account the safety of their employees.

In this paper, the seismic risk management methodology by Takahashi et al. (2002, 2004) is extended to multiple industrial buildings. As an index to express the safety of the employees, we estimate the probabilities that each building incurs several structural damage states. The selected buildings are assumed to be located near the ten major harbors in Japan, such as Tokyo, Oosaka, Niigata, Kochi ports and so on.

2. METHODOLOGY

Generally, building is surrounded by a number of seismic sources. Even if it is confined one's attention to only one seismic source, it is impossible to determine the certain magnitude to be occurred from that particular source. To estimate the probability of structural damage, it is necessary to take account for all possible earthquakes surrounding the building, i.e., all seismic sources and various magnitudes.

For a given lifetime t_{life} of a building, the probability of failure $P_{Fail}(t_{life})$ is estimated as

$$P_{Fail}(t_{life}) = 1 - \prod_{AllEQ} \{1 - P_{Fail}(EQ, t_{life})\} \qquad (1)$$

where $P_{Fail}(t_{life})$ is defined as the building is fallen down at least one time under considering all possible earthquakes EQ during t_{life}. $P_{Fail}(EQ, t_{life})$ is the probability of the building fallen down at least one time due to specific earthquake event EQ for t_{life}.

$$P_{Fail}(EQ, t_{life}) = \sum_{n=1}^{\infty} P_{EQ}(n, t_{life})\{1 - P_{Safe}(EQ)^n\} \qquad (2)$$

where $P_{EQ}(n, t_{life})$ is the probability of earthquake event EQ, n is the number of occurrence of the earthquake EQ for t_{life}. This term corresponds to probabilistic model of earthquake occurrence, and it can account not only for historical earthquake data but also for recently acquired information on activities of seismic sources, such as HERP or the research report of the National Institute for Land and Infrastructure Management (NILIM, 2003) in Japan.

$P_{Safe}(EQ)$ is the probability of safety of the building under the earthquake event EQ. This term should be computed for a specified magnitude m_j in a given source. And relevant processes are illustrated in Figure 1: fault rupture in the seismic source, elastic wave propagation, surface soil amplification, and dynamic response of building.

As mentioned previously, in theory, any simulation model can be used in estimating the probability of safety $P_{Safe}(EQ)$ in Equation (2). However, in practice, an engineer is supposed to prepare a "menu" including several "courses" corresponding to needs from clients, i.e., building owners. Some clients may need the most exact solutions with much money, but others with small budgets may request rough estimation. Figure 2 gives an example of a menu with three courses, cheap, middle and expensive. If the expensive course is ordered, an engineer can spend much time in the specification of the parameters and computation, and give one of the most reliable solutions. On the other hand, if the cheap course is requested, the engineer can show the result instantly and cheaply with simple simulations. Figure 2 is just current example, and it should be updated by reflecting the progress of simulation models and computation technologies in relevant academic fields aiming to provide clients with better decision- making tools with less expense.

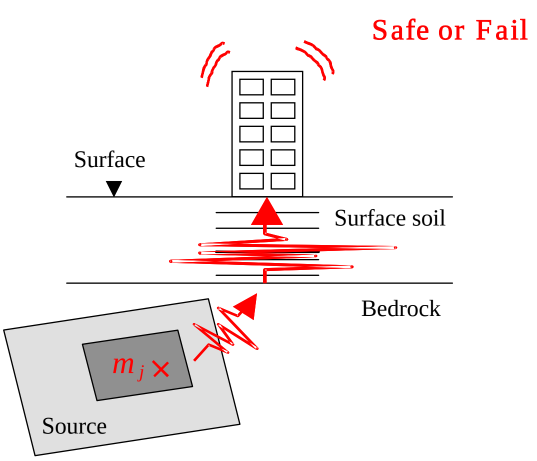

Figure1. Events from fault rupture to damage states: safety or failure

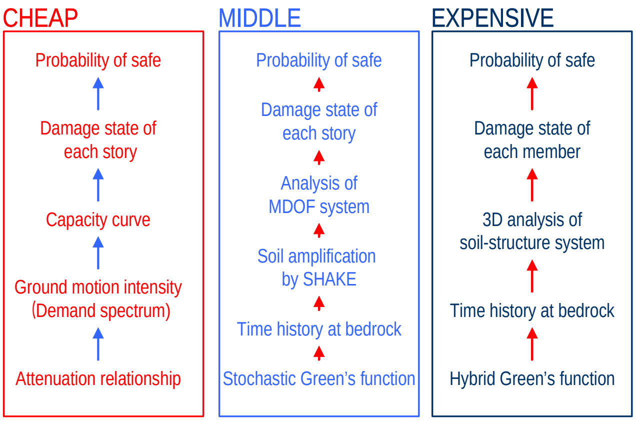

Figure2. Example of current simulation models for the computation of the probability of safe

In a decision-making on the priority of earthquake retrofit of multiple buildings, the simulation models of the "cheap course" in Figure 2 may be currently adequate in terms of computation time and cost. Following Takahashi (2004), the simplified simulation models in the "cheap course", which utilizes Capacity Spectrum method, is adapted for the case study in the next section.

3. APPLICATION

3.1 Buildings under consideration

A two-story existing industrial building is considered here (Figure 3). This building consists of steel frames and steel bracings, and has a total area of about 2,900 m^2. The structure was designed in 1966 based on the old Japanese building code. Then the remaining lifetime of the building is assumed to be 30 years, that is, t_{life} = 30 years in Equations (1) and (2). For the detailed information of this building, refer to the previous study (Murachi et al, 2005), which evaluated the life-cycle cost using the "middle course" simulation in Figure 2. In this study, the probability of safety is estimated only for the existing building. The comparison with the damage probability of upgraded buildings will be addressed in the future study.

Figure3. Selected industrial building

Ten identical industrial buildings mentioned above are distributed near the ten major harbors in Japan, as shown in Figure 4. Geomorphological land classification of each location can be assigned by referring to the Digital National Land Information (1992), as shown in Table 1.

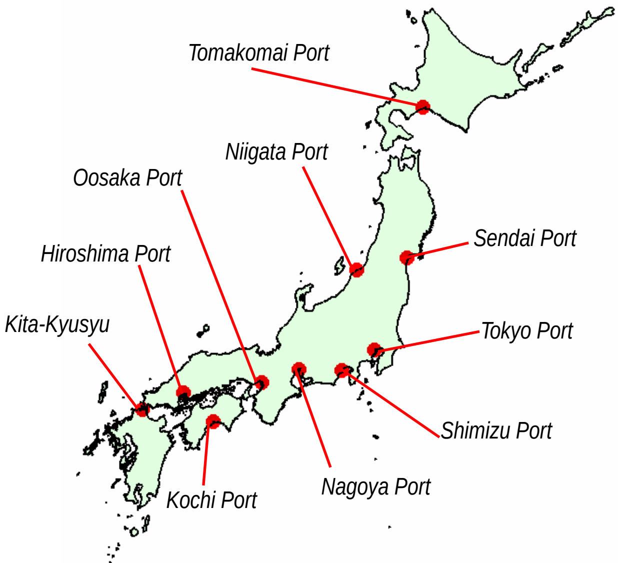

Figure4. Building located near the ten major harbors

Table1.Land classification at each location

No.	Location	Land Classification
1	Tomakomai Port	Delta (sand)
2	Sendai Port	Delta (mud, clay)
3	Niigata Port	Delta (sand)
4	Tokyo Port	Reclaimed land
5	Shimizu Port	Delta (sand)
6	Nagoya Port	Reclaimed land
7	Oosaka Port	Delta (sand)
8	Hiroshima Port	Reclaimed land
9	Kochi Port	Reclaimed land
10	Kita-Kyusyu Port	Delta (mud, clay)

3.2 Activity of seismic source

We make use of the seismic models constructed by NILIM (2003) in this analysis. NILIM (2003) listed numerous seismic sources around Japan, and grouped them into three types:

(A) Plate-boundary sources,
(B) Active faults, and
(C) Back-ground sources.

The Poisson model, which is one particular form of renewal models, is adequate for earthquakes that frequently occur during the lifetime of the building. However, for infrequent earthquake, a non-Poisson renewal model may be more appropriate. Among non-Poisson renewal models, the Brownian Passage Time (BPT) model (Matthews, 2002) has been applied to long-term estimation of earthquake probabilities by WGCEP (1999) and HERP.

Table2. Seismic sources affected for each site *M: Magnitude, D: Minimum Distance from the source

(A). Shimizu Port

No.	Seismic Source	M	D (km)	Annual Probability	$P_{EQ}(1,30)$	
					Poisson	Poisson+BPT
1	Tokai earthquake	8	11.64	2.2E-01	2.2E-01	7.8E-01
2	Kanto earthquake	7.9	43.24	1.3E-01	1.3E-01	3.0E-03
3	Tou-Nankai earthquake	8.1	79.95	2.9E-01	2.9E-01	6.5E-01
4	Fujigawa-Kakou active fault zone	8	15.68	2.7E-02	2.7E-02	1.9E-01
5	Tanna acrive fault zone	7.4	45.87	2.5E-02	2.5E-02	8.6E-40
6	Itoigawa-Sizuoka Tectonic Line active fault zone	8	60.72	3.0E-02	3.0E-02	1.5E-01
7	Kannawa Kozu -Matsuda zctive fault zone	8	62.91	1.0E-02	1.0E-02	3.8E-02
8	Isehara active fault	7	89.87	9.1E-03	9.1E-03	1.0E-06
9	Atera active fault zone	7.9	101.49	1.7E-02	1.7E-02	6.8E-11
10	Darumayama active fault zone	6.8	27.64	1.2E-02	1.2E-02	1.2E-02

(B). Kochi Port *MTL: Mid Techno Line active fault system

No.	Seismic Source	M	D (km)	Annual Probability	$P_{EQ}(1,30)$	
					Poisson	Poisson+BPT
1	Nankai Earthquake	8.4	29.21	1.1E-02	2.8E-01	5.2E-01
2	MTL, Shikoku-Kii zone, North foot part of the Ishizuchi Mt.	7.6	51.53	1.0E-03	3.0E-02	2.0E-01
3	MTL, Shikoku-Kii zone, South foot part of the Sanuki Mt.	8.2	53.46	1.3E-03	3.7E-02	2.3E-02
4	MTL, Kawakami active fault zone	6.9	67.41	7.1E-04	2.1E-02	5.0E-02
5	MTL, Iyo active fault zone	7	77.72	1.8E-04	5.4E-03	6.8E-20
6	Nagao active fault zone	7.1	93.28	5.9E-05	1.8E-03	1.9E-03
7	Tokushima plain active fault zone	6.7	97.33	6.7E-04	2.0E-02	8.4E-02
8	Tunatsukemori active fault	6.6	42.36	5.9E-04	1.7E-02	1.7E-02
9	Yasuda active fault	7.1	42.37	2.2E-03	6.3E-02	6.3E-02
10	Gyodozaki active fault	6.9	58.68	7.7E-04	2.3E-02	2.3E-02

(C). Kita-Kyusyu Port

No.	Seismic Source	M	D (km)	Annual Probability	$P_{EQ}(1,30)$	
					Poisson	Poisson+BPT
1	Kokura east active fault	6.9	1.44	4.5E-04	1.4E-02	5.7E-10
2	Kikukawa active fault	7	31.12	1.4E-04	4.3E-03	5.9E-03
3	Nishiyama active fault zone	7.3	33.32	1.0E-04	3.0E-03	2.7E-18
4	Kego active fault zone	7	54.68	6.3E-05	1.9E-03	8.6E-03
5	Minoo active fault zone	7.2	65.18	7.7E-04	2.3E-02	7.1E-29
6	Beppu-Haneyama active fault zone	7.9	76.63	5.0E-04	1.5E-02	2.1E-01
7	Futagawa active fault zone	7.1	109.71	1.6E-04	4.8E-03	5.0E-02
8	Fukuchiyama active fault zone	7	19.11	3.1E-04	9.3E-03	9.3E-03
9	Sibuki active fault	6.8	38.71	4.0E-05	1.2E-03	1.2E-03
10	Kamatouge - Koishiwara	6.6	43.35	5.3E-05	1.6E-03	1.6E-03

In NILIM (2003), for plate-boundary sources, the occurrence rates of infrequent earthquakes are estimated utilizing the BPT model. For active faults, if the information on the time of the last earthquake is available, the BPT model is also used. For the other earthquakes, the Poisson model is adapted. As an example, Table 2 lists the ten seismic sources, which are the most influential on Shimizu, Kochi and Kita-Kyusyu port, respectively. Notably, only the plate-boundary sources and the active faults appear in Table 2. The back-ground sources turn out to be much less affective, and are omitted here.

3.3 Simulation for probability of safety

In "cheap course" in Figure 2, Capacity Spectrum method is applied to the estimation of the dynamic response of a building (Takahashi, 2004). To evaluate the demand spectrum $S_v(T,h=5\%)$ at a building site from each seismic source, the attenuation relationship by Yamauchi et al. (2001) is used here.

$$\log_{10} S_v(T,h=5\%) = b_0(T)+b_1(T)M+b_2(T) - \log_{10} r + b_4(T)h + c_i(T) \quad (3)$$

where M is magnitude, r is minimum distance from sources (km), h is depth from hypocenter (km). $b_0(T)$, $b_1(T)$, $b_2(T)$ and $b_4(T)$ are the coefficients determined from regression analyses. $c_i(T)$ is the site factor that accounts for geomorphological land classification at each site, and is given for the eleven land categories. Using geomorphological land classifications for each study location (see Table 1), $b_0(T)$, $b_1(T)$, $b_2(T)$, $b_4(T)$ and $c_i(T)$ are obtained from the figures in Yamauchi et al. (2001).

The two-story steel building with steel bracings is modeled as a two-degree of freedom system. To depict the capacity curve of the equivalent SDOF system (Figure 5), the push-over analysis is performed on the 2 DOF model. Then, peak dynamic response of the equivalent SDOF system is evaluated as the intersection of the capacity curve and demand spectrum. Peak response of the 2 DOF system is estimated by multiplying the peak response of the SDOF model by the participation function of the original 2 DOF model.

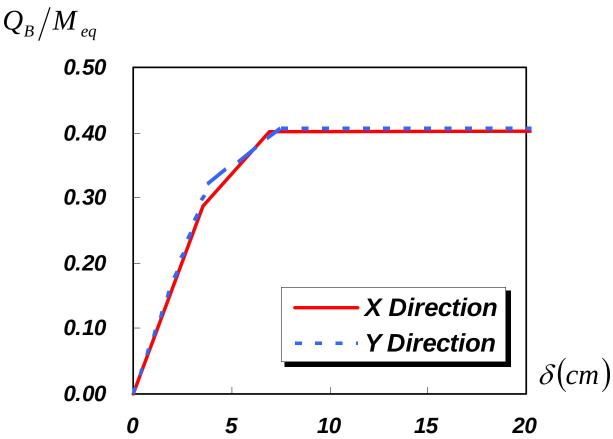

Figure5. Capacity curve for the industrial building

Based on the peak inter-story drift ratios of the 2 DOF model, a probability of safety $P_{Safe}(EQ)$ in Equation (2) is estimated for each seismic source using fragility curves by FEMA (1999). In order to evaluate the two levels of severity of casualties, one is the dead and the injured and the other is only dealing with the dead, probabilities of two damage states of the building are estimated: damage states of "at least moderate" and "at least extensive" (Table 3).

Table 3 indicates that Shimizu port exhibits the highest damage probabilities, i.e., the employees at Shimizu port are exposed to the most intensive hazard. Therefore the upgrade of the building at Shimizu port is the most urgent among those of the ten facilities. The buildings at Oosaka and Kochi ports are ranked in the second and third, respectively. The damage probabilities estimated applying only

Poisson model and ones applying BPT and Poisson models are listed in the third and fourth columns, respectively, in Table 3 (A) and (B). At all sites other than Tokyo port, the probability based on both BPT and Poisson models (fourth column) are higher than one based on only Poisson model (third column). On the other hand, at Tokyo port, the probabilities based on BPT model are much smaller than the other one. This is because the elapsed time since the last earthquake is much shorter than its interval time, for plate-boundary sources and active faults around Tokyo port, and BPT model can reflect such time dependency of the occurrence rates of earthquakes.

Table3. Probability of structural damage

(A). Probability of ***"at least moderate"*** damage state of building in the next 30 years. (%)

No.	Location	Poisson	Poisson + BPT
1	Tomakomai Port	1.82	11.06
2	Sendai Port	8.68	17.15
3	Niigata Port	0.86	3.41
4	Tokyo Port	11.39	1.00
5	Shimizu Port	49.98	91.68
6	Nagoya Port	11.62	19.42
7	Oosaka Port	41.01	63.57
8	Hiroshima Port	1.02	1.23
9	Kochi Port	29.67	52.16
10	Kita-Kyusyu Port	2.72	8.38

(B).Probability of ***"at least extensive"*** damage state of building in the next 30 years. (%)

No.	Location	Poisson	Poisson + BPT
1	Tomakomai Port	0.27	1.94
2	Sendai Port	0.52	1.30
3	Niigata Port	0.04	0.23
4	Tokyo Port	0.39	0.01
5	Shimizu Port	19.79	65.47
6	Nagoya Port	0.28	0.13
7	Oosaka Port	5.96	11.33
8	Hiroshima Port	0.00106	0.00026
9	Kochi Port	9.93	17.97
10	Kita-Kyusyu Port	0.15	0.03

4. CONCLUSION

In this paper, the seismic risk management methodology for single buildings, proposed by Takahashi et al. (2002, 2004), is extended to multiple buildings. To focus on life safety, we formulate the probabilities that a building incurs some damages during its lifetime, by extending the equation of life-cycle cost by Takahashi et al. (2002, 2004). In the case study, the selected industrial buildings are assumed to be distributed near ten major harbors in Japan. The probabilities of two damage states, "at least moderate" and "at least extensive", of each building in the next 30 years are estimated as an index to evaluate the safety of employees. In the analysis, up-to-date knowledge obtained in the field of seismology and earthquake engineering is beneficially utilized, e.g., seismological models by NILIM (2003) including BPT model, and Capacity Spectrum method for earthquake response of buildings. The results evaluated in this paper are one of the useful information for the manager of an organization to prioritize the upgrading of its existing multiple buildings.

The models utilized in the case study may be currently reliable, because they were constructed by sophisticating existing models. However, it is almost impossible to obtain models that simulate physical phenomena perfectly. Thus the engineers would be expected to update their models according to the progress in the related academic fields. For example, in March 2005, HERP published more detailed seismological models after NILIM (2003). Such models would be introduced in the future study.

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