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Life-cycle cost analysis for nuclear power plants with seismic isolated system

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ABSTRACT

This paper presents the nuclear power plant (NPP) life-cycle cost analysis. The NPPs requiring higher safety level need to manage earthquakes by applying the seismic isolation systems. The objectives of this paper include studying (a) considerations for NPP life-cycle cost analysis; (b) effect of seismic isolation system installation on the NPP life-cycle cost analysis with earthquake; and (c) cost-benefit analysis when applying the seismic isolation systems to NPP.

1. INTRODUCTION

Since the last few decades, the number of nuclear power plants (NPPs) has increased with relatively low electric cost demands. In order to extend the service life of the NPP ensuring the structural safety under structural deteriorations and various natural hazard risks, the importance of effective and efficient management of NPP has been recognized (IAEA 1998). Moreover, the systemic efforts are being required to reduce the potential loss of NPPs resulting from the natural hazard including earthquakes, hurricane and flooding since the Fukushima accident (IAEA 2013).

Earthquake risk of building structures can be mitigated through appropriate seismic isolation system installation (Kelly 1986). It has been known that a seismic isolation system can lead to reduction of the deleterious effect on ground motion induced by earthquakes, and structural safety can be improved (Komodromos 2000). General recommendations to apply the seismic isolation system for NPPs are addressed in Kammerer et al. (2012).

In this paper, NPP life-cycle management is reviewed. Furthermore, cost-benefit analysis when applying the seismic isolation systems to NPP, and effect of seismic isolation on the NPP life-cycle cost analysis with earthquake are introduced.

2. NPP LIFE-CYCLE MANAGEMENT

Life-cycle management is a systemic method to address costs effectively and

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ensure the structural safety under budget constraint (EPRI 2001, Frangopol and Liu 2006). As shown in Fig. 1, life-cycle of NPP considers all the phases from design to decommissioning (IAEA 2002). Although the initial design life is predetermined, the service life of a NPP can be extended through the high quality inspection, maintenance and justification for life extension. When the required cost for service life extension is not economically feasible, and/or the safety level of NPP can be lower than the predefined one, the NPP can cease operating for decommissioning.

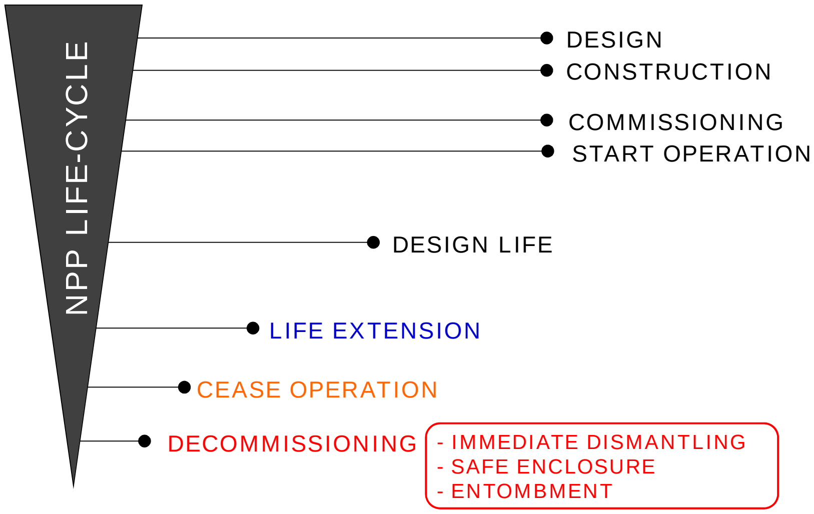

Fig. 1 Life-cycle of nuclear power plant (adapted and modified from IAEA (2002))

Life-cycle management for NPP is the integrated work covering operation, maintenance, regulatory, environmental and economic planning activities as well as engineering (EPRI 2001). Table 1 summarizes the general and specific inputs of life-cycle management for NPP.

Table 1 Inputs for life-cycle of nuclear power plant (adapted from IAEA(2002))

General inputs	• Management: Safety, Asset, Ageing, Quality, Knowledge, Performance, Human resource, Fuel cycle/waste, License, Environmental, Risk, Stakeholder • Preventive maintenance, Periodic safety reviews • Economic optimization
Life-cycle stage inputs	• Design strategies and criteria • Social impact • Self-managed or Turnkey during construction, commissioning, operation ordecommissioning • Operating strategies • Decommissioning options • Statutory and regulatory requirements • Utility business objectives

Significant efforts to address ageing, safety and performance management for civil infrastructure management have been made. However, the development of more practical and effective approaches for NPP life-cycle management is still challengeable.

3. EFFECT OF SEISMIC ISOLATION ON THE NPP LIFE-CYCLE COST ANALYSIS

Seismic isolation can reduce the response of a structure to earthquake ground motion (Kammerer 2012). Fig. 2 shows the NPP with the seismic isolation system installed between the foundation and the superstructures.

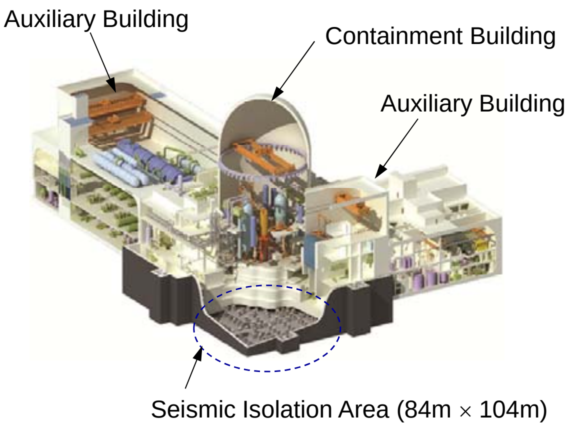

Fig. 2 NPP with seismic isolation system

NPPs are generally inspected and maintained periodically by statutory and regulatory requirements (IAEA 2004). If the damaged structures, systems and components (SSCs) are found by inspection, the associated SSCs are repaired or replaced. However, the structural safety of an entire NPP decreases gradually over time, due to the fact that there must be non-replaceable SSCs of NPP (e.g., reactor vessel, containment), and repair and replacement of limited SSCs cannot lead to the initial structural safety of an entire NPP. The deterioration rate can be reduced, and NPP safety based on inspection results will be predicted more accurately. However, the deterioration of the NPP cannot be avoided.

Furthermore, the structural safety is affected by extreme events such as earthquake, flood, and hurricane, among others. These events can lead to the sudden drop of the structural safety. Fig. 3 shows the time-dependent structural safety with and without seismic isolation system. As shown in Fig. 3(a), if the earthquake occurs at time t_{ea}, and the structure is not seismically isolated, then the safety deceases from S_{ini} to $S^{(0)}_{ea}$, the time $\Delta t^{(0)}_{rp}$ is required to inspect and repair the structure. In Fig. 3(b), the decrease of safety from S_{ini} to $S^{(1)}_{ea}$ and the time for inspection and repair $\Delta t^{(1)}_{rp}$ are associated with the seismically isolated structure, respectively.

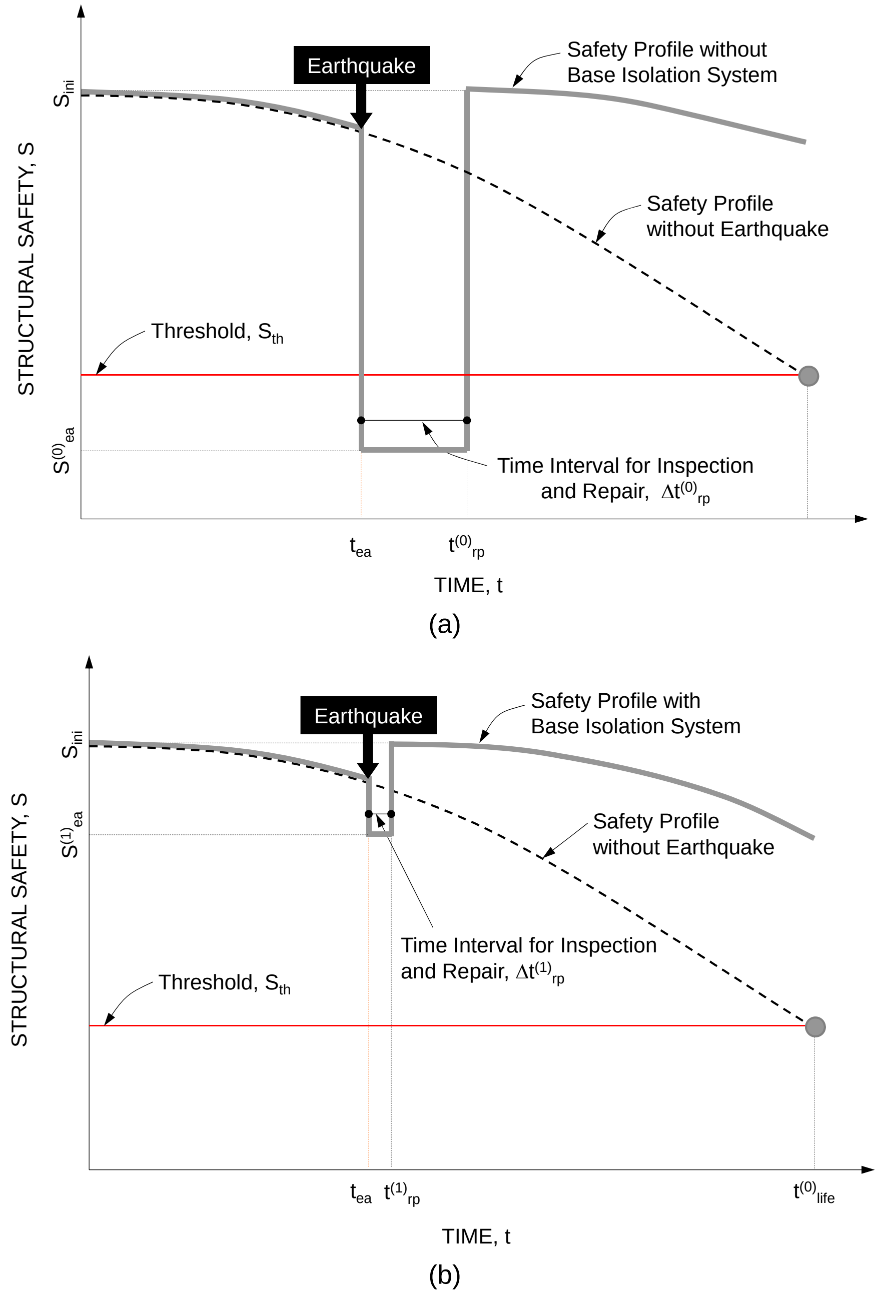

Fig. 3 Structural safety profile: (a) without seismic isolation system; (b) with seismic isolation system

4. COST-BENEFIT WHEN APPLYING SEISMIC ISOLATION SYSTEMS TO NPP

If the seismic isolation system is designed and installed appropriately, damage from earthquake can be reduced and avoided. As smaller degree of damage occurs, less cost is required (Ellingwood and Mori 1997). For this reason, there will be the cost benefit by installing the seismic isolation system under earthquake risk. This cost-benefit C_{ben} is expressed as

$$C_{ben} = (C^{(0)}_{rp} - C^{(1)}_{rp} + C_{loss})\, P_{ea} - C_{instl} \tag{1}$$

where P_{ea} = probability of earthquake occurrence during the service life of a structure; $C^{(0)}_{rp}$ = cost associated with inspection and repair to improve the structural safety after earthquake when the seismic isolation system is not installed; $C^{(1)}_{rp}$ = cost associated with inspection and repair after earthquake for a seismically isolated structure. C_{loss} is the monetary loss due to the sudden drop of the structural safety considering human injuries, user cost, and et al. In Eq. (1), C_{loss} is considered only for the non-seismically isolated structure. Furthermore, C_{instl} = cost for initial design, installation and maintenance cost of the seismic isolation system. Generally, these costs are under uncertainty so that they can be treated as random variables. In this case, the probability that the seismic isolation provides the cost-benefit for the owner of the structure P_{ben} is

$$P_{ben} = P(C_{ben} \geq 0) \tag{2}$$

Assuming that P_{ea} is lognormally distributed with the mean of 1/1000 and standard deviation of 1/2000, respectively, and C_{instl} is equal to 1.0, the probability density function (PDF) can be obtained as shown in Fig. 4, where C_{temp} is $C^{(0)}_{rp} - C^{(1)}_{rp} + C_{loss.}$

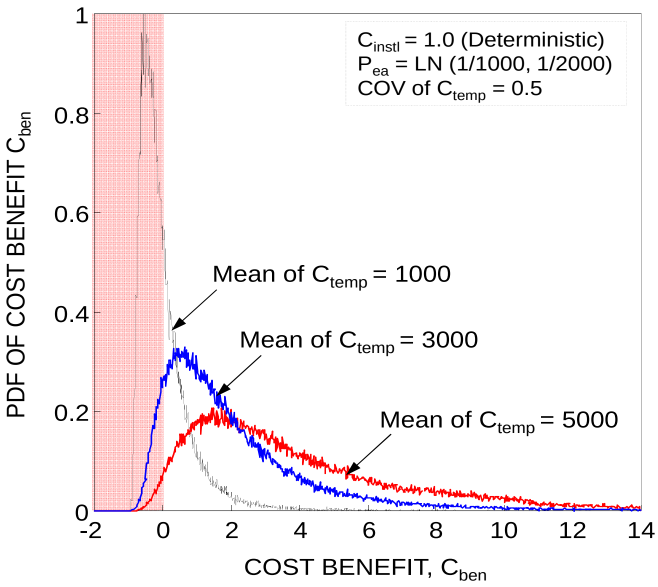

Fig. 4 PDF of cost benefit

5. CONCLUDING REMARKS

This paper presents (a) the review of NPP life-cycle management; (b) the effect of seismic isolation system on the structural safety under earthquake risk; and (c) the approach for cost-benefit analysis when the seismic isolation system is applied to NPP. For practical use of the concepts and results presented in this paper, significant efforts including rational cost estimation for loss resulting from earthquakes, inspection and repair, and prediction of earthquake occurrence rate and the associated magnitude should be made.

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