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# Seismic Probabilistic Safety Assessment (PSA) for Nuclear Power Plants (NPP) considering Adjacent Landslide Hazard

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## 1. Introduction

The 2011 Fukushima Daiichi NPP accident showed the need to explore various multi-hazard scenarios in which the seismic hazard induces other hazards. Especially, this accident clearly illustrated that the landslide close to the NPP could result in a considerable damage to the NPP safety [1]. Therefore, this paper studied a practical approach for the earthquake-induced landslide PSA with respect to the NPPs subject to the seismic hazard. The approach was devised within the current seismic PSA framework.

## 2. Seismic PSA

In the current methodology [2], the seismic risk for a NPP (i.e., annual core damage frequency (CDF)) is evaluated by convolution of the hazard curve and the plant-level fragility curve as follows:

$$CDF = \int P_f(a) \cdot \left| \frac{dH(a)}{da} \right| da \qquad (1)$$

in which $a$ is a seismic hazard intensity parameter, $P_f(a)$ is the plant-level fragility curve, and $H(a)$ represents the hazard curve. The hazard curve expresses annual exceedance of the probability in a domain of the intensity measure. The component fragility curve is obtained by using empirical, experimental, and/or numerical simulation data. It represents the conditional probability of failure in seismic hazard's intensity. The plant-level fragility curve is evaluated by employing a systems analysis technique such as event and fault trees. In addition, a seismic PSA also considers random failure events that are not caused directly by seismic hazards. This failure data is in general represented as an annual failure rate.

## 3. Slope Failure and Run-out

The seismic slope fragility analysis can be conducted with the Newmark-based rigid-block model to assess the slope stability under the seismic event. The model to obtain the permanent displacement for assessing the slope stability in this study uses an equation proposed by Jibson [3]. The equation mainly consists of a six parameters: cohesion ($c$); friction angle ($\varphi$); slope angle ($\alpha$); soil unit weight ($\gamma$); slope normal thickness of failure surface ($t$); and the percentage of failure thickness that is saturated ($m$) (refer to Fig. 1). The failure criterion is estimated based on the observed direct correlation between the predicted Newmark displacements and the slope failure probabilities. Finally, the slope seismic fragility is calculated using MCS-based approach.

From a plant safety perspective, the distance between the plant and the nearby slope is one of significant elements to evaluate the potential risk. Thus, this study utilizes the geometrical approach of empirical method to estimate the travel distance of the earthquake-induced landslide occurred. The minimum shadow angle ($\beta$) concept [4] is used as an empirical measure to express the mobility of the landslides (see Fig. 2). The effect of mobility of landslide is considered along with the seismic slope fragility ultimately for quantifying the plant seismic safety of CDF.

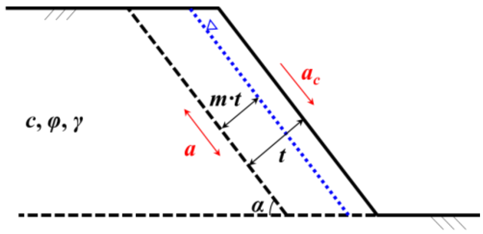


Fig. 1. Sliding block model used for seismic slope fragility analysis

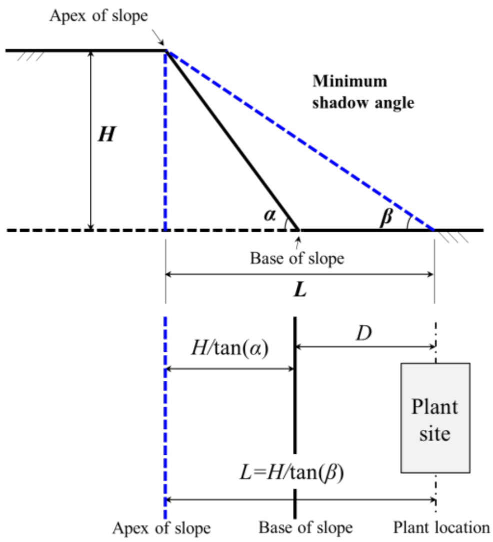


Fig. 2. Geometrical relation between slope and plant site

## 4. Numerical Example

### *4.1. Example site: Ulchin NPP unit 5 & 6*

Fig. 3 shows the site of Ulchin NPP unit 5 & 6 and a conceptual sketch of their configuration and adjacent slope. The properties of the slope considered are: $c$ = 40 kPa, $\varphi$ = 30°, $\alpha$ = 45°, $\gamma$ = 19 kN/m$^3$, $t$ = 3 m, $m$ = 0 (no pore-water pressure), and $\gamma_w$ = 9.807 kN/m$^3$. The parameters for the discharge analysis resulted from slope failure are defined as: $D$ = 100 m, $H$ = 100 m and $\beta$ = 25°. For the slope fragility ($P_{f1}$) and its run-out probability calculation ($P_{f,SF}$), all parameters are regarded as random variables and are assumed to follow normal distributions having a certain coefficient of variation. The SSCs which can be likely damaged by the adjacent slope failure and its discharge are identified as 154kV switchyard for offsite power (SOP), condensate storage tank (CST) and auxiliary building (AB).

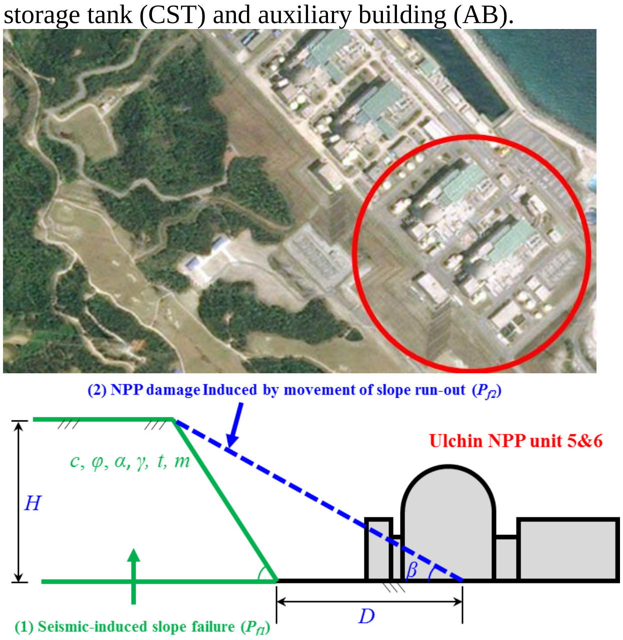


Fig. 3. Site of Ulchin NPP 5 & 6 and adjacent slope

### *4.2. Seismic PSA results*

The original CDF value for Ulchin NPP unit 5 & 6 [5] is evaluated as 9.82E-06 (/year). But, by considering the adjacent slope failure and its run-out, this deteriorates the original seismic fragility of SOP, CST and AB ($P_{f,SSC}$ : original; $P_{f,SSCu}$: updated) as shown in Fig. 4. Consequently, CDF owing to the probable threat of seismic slope failure adjacent to the NPP is increased by about 57.1% (refer to Table 1). The degraded seismic fragilities of the CST and the AB similarly contribute to the increase in CDF.

Table 1: Increase of the CDF due to slope failure close

| Affected SSCs | CDF (yr-1) | CDF increase ratio (%) |
|---|---|---|
| SOP | 9.85E-06 | 0.25 |
| CST | 1.25E-05 | 27.09 |
| AB | 1.28E-05 | 29.89 |
| All (SOP, CST, AB) | 1.54E-05 | 57.08 |

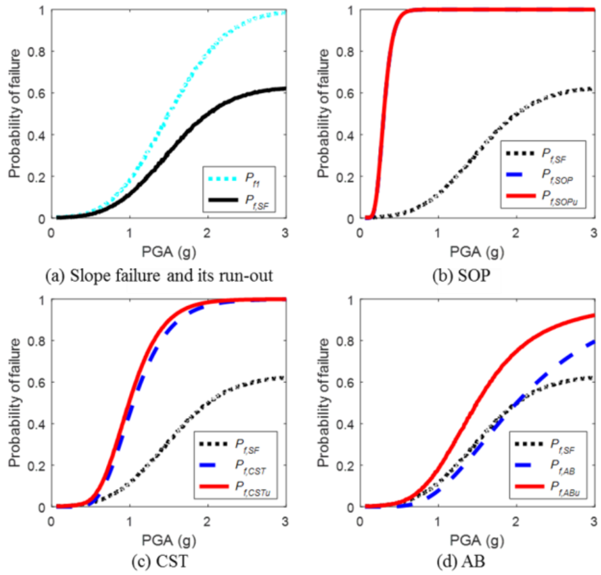


Fig. 4. Degraded fragility curves for SOP, CST and AB considering slope vulnerability causing a potential damage to NPP

## 5. Summary and Conclusion

An approach for the earthquake-induced landslide PSA was studied for the NPP under seismic hazards within the current seismic PSA framework. For the application example, the proposed approach adopted the Ulchin NPP unit 5 & 6 in Korea and the peripheral slope. The assessment result showed the quantitative probabilistic effects of adjacent slope failure and its discharge to the CDF of NPP under the earthquake event. In the future, this study is expected to aid in the risk mitigation plan for the NPP potentially damaged by the adjacent slope vulnerability.

## ACKNOWLEDGEMENTS

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