Framework for Probabilistic Flood Hazard Assessment for Nuclear Related Facilities

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1. Introduction

Siting, licensing, and engineering nuclear power related facilities, such as a nuclear power plant (NPP) or a radioactive waste disposal site require safety analyses that include the effects of extreme events, such as flooding. For NPPs, there have been three recorded case histories of major flooding events that disrupted operations.

In 1999, the Gironde River flooded the Blayais NPP as a result of extratropical storm Martin, causing a loss of the off-site power supply and knocking out several safety-related systems. In 2011, the Missouri River flooded the Fort Calhoun nuclear power station, eventually leading to a cold shutdown even though the station was designed for a 500 year flood. Figure 1a shows the level of flooding at the power station. A flood barrier was installed around the nuclear and turbine islands, but human errors led to a barrier breach. Earlier in the same year, the Fukushima nuclear power plant campus was inundated by a tsunami, as shown in Figure 1b. As a result, Fukushima Daiichi #1, #2, and #3 are in the process of being decommissioned and the surrounding area has largely been abandoned.

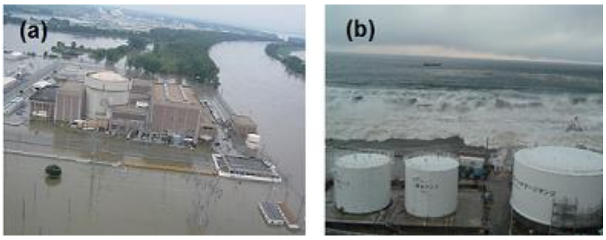

Fig. 1. Nuclear power plants that experienced extreme flooding events and an interruption in operations, (a) Fort Calhoun Station and (b) Fukushima, Japan.

Characterization of flood hazards and siting for radioactive waste disposal and storage facilities is similar to that for NPPs [1-7]. Thus, facilities such as surface and underground radioactive waste storage facilities also follow a similar framework and are also exposed to similar flood hazards. Underground radioactive waste storage facilities, such as deep geologic repositories, require surface infrastructure which can be affected by external flooding events. The aforementioned NPP flooding incidents highlight the disastrous effects flood hazards can have on radioactive waste related facilities, bringing into question the methodology used in accounting for flood hazards.

The current suggested methodology in accounting for design basis flood hazards by the United States Nuclear Regulatory Commission (NRC) is hierarchical hazard assessment (HHA). HHA is a procedure that determines the level of NPP site flood protection by iteratively constraining a Probable Maximum Flood (PMF) event. The PMF is generally derived from individual events including local intense precipitation, riverine flooding, dam failure, storm surge, seiche, ice-induced flooding, channel migration or diversion, and tsunami. In its current form, HHA can be considered a deterministic approach. As suggested by NUREG/CR-7046 [7], the basic steps in an HHA are outlined in Figure 2. The procedure basically starts with an estimate of the probable maximum precipitation (PMP). The PMP is combined with conservative assumptions to estimate a probable maximum flood (PMF) and resultant water surface elevation. If this surface water elevation does not exceed critical elevations for structures, systems, and components, then the process terminates as safety is demonstrated with conservative assumptions. If the water surface elevation exceeds critical elevations for structures, systems, and components, then a re-evaluation of the initial assumptions is performed to determine if an assumption could be converted to site specific data. If not, then flood protection for structures, systems, and components needs to be implemented. If site specific data is available, the PMF is estimated again using the new data and the process is repeated.

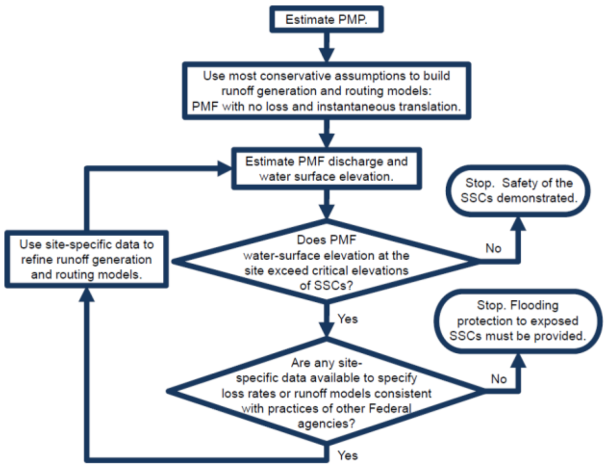

Fig. 2. Flowchart demonstrating the HHA applied to flood hazards from a PMF event.

However, the International Atomic Energy Agency suggests the use of both deterministic and probabilistic approaches in evaluating design basis flood hazards.

Although a comprehensive Probabilistic Flood Hazard Assessment (PFHA) methodology has not yet been developed, the NRC has suggested applying the framework that other U.S. governmental agencies have used in analyzing flood hazards for their projects, such as dam breaching. This approach generally consists of combining the results from multiple flood hazard analyses to produce a hydrological hazard curve, as demonstrated in Figure 3. The design basis flood is then evaluated by subjectively combining the results of these hydrological hazard curves and selecting an appropriate level of risk in terms of annual exceedance probability. The American Nuclear Society has recommended an average annual probability-of-exceedance less than 10-6 as an acceptable goal for selection of flood design bases. However, literature and state-of-practice does not clarify how these hazard curves are combined other than by the consultation of hydrological experts. Moreover, how does one combine a flooding event caused by an extremely large storm, with a flooding event from a tsunami?

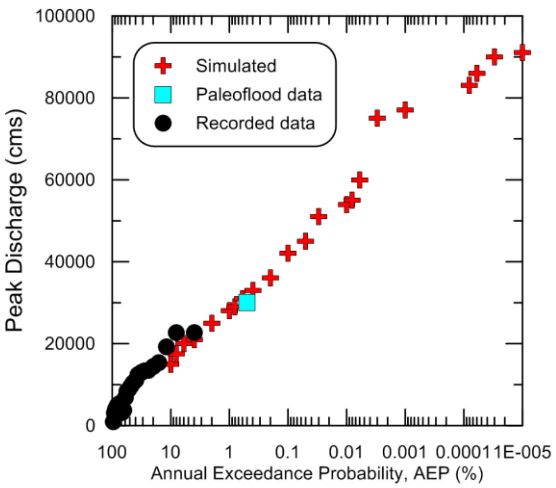

Fig. 3. Example hydrological hazard curve showing the multiple methods used for construction.

Given this backdrop, this paper attempts to develop a more comprehensive PFHA methodology. This methodology is inspired from the techniques used in modern probabilistic seismic hazard analysis (PSHA). A PSHA framework is proposed is because it can more easily integrate seismically induced flooding, can be performed in a relatively more computational manner, can be deaggregated to evaluate controlling parameters, and partially removes some of the subjective judgement suggested in other methods.

2. Probabilistic Seismic Hazard Analysis

Like PFHA, there is no generally accepted Probabilistic Tsunami Hazard Analysis (PTHA) procedure. However, most frameworks consider PTHA to be an extension of PSHA. An important feature of PSHA is that the procedure can be inverted, or deaggregated, to identify controlling source parameters for hazard evaluation. Generally, PSHA is defined as:

$$\lambda(IM > x) = \sum_{i=1}^{N_s} \lambda(M_i > m_{min}) \iint P[IM > x|m,r] f_{Mi}(m) f_{Ri}(r)\, dr\, dm$$

where λ(IM > x) = total average exceedance rate for intensity measure, IM (such as peak ground acceleration); N_s = number of potential sources (faults); $\lambda(M_i > m_{min})$ = average rate of threshold magnitude exceedance, also known as a recurrence relationship; M, m = magnitude; and R, r = source to site distance. Although this method has been criticized for its physical interpretations, it is currently used for evaluating seismic hazards at NPP sites. A PTHA methodology that is based on the PSHA definition would be difficult to integrate with the current state-of-practice in flood frequency analysis, which basically ranks flooding events.

The attenuation relationship, P[IM > x | m, r], in the PSHA definition also has meaning in flood frequency analysis. The mirrored relationship in hydrology would be the unit hydrograph. Hydrologists use the unit hydrograph to convert storm rainfall intensities to riverine discharge. However, the use of unit hydrographs to estimate flood discharge has been criticized as unit hydrographs are linear tools while extreme flooding is considered to be a nonlinear process. One issue in flooding analyses that the PSHA definition does not capture is the application of joint probability distributions. This arises from situations where for example, riverine flooding and dam failure occur as a result of the same intense precipitation event. Another example would be the occurrence of a large enough earthquake to start a tsunami and to cause upstream dam failure.

3. Flooding Mechanisms

The pre-dominant flooding mechanisms this paper will consider are shown in Figure 4. Under certain conditions, a significant earthquake can fail a dam. Dam failure can lead to the release of impounded water downstream thus increasing the riverine height. For coastal sites, considerable inundation can come from storm surges when the storm is large enough. Large significant storms can also cause riverine depth to rise as well as runoff. Additional sources of flooding, such as ice-induced flooding, tsunamis, landslides, and seiches are not considered herein. Structural failure of dams is also not considered.

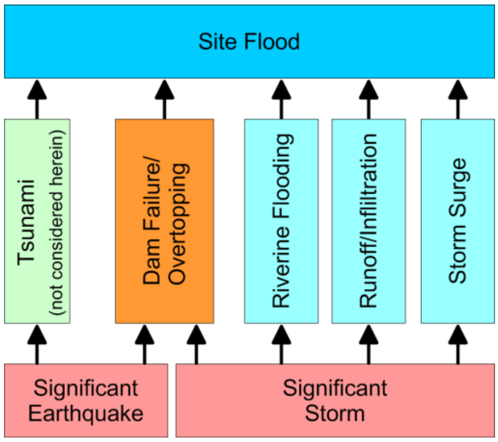

Fig. 4. Pre-dominant flooding mechanisms considered at radioactive waste disposal site.

Storms can have a variety of engineering parameters or descriptors, such as precipitation amount, duration of storm, wind velocities, and pressure variation. For the proposed framework, precipitation amount, measured in length as precipitation depth, Ψ, duration of precipitation, measured in time, δ, and wind spend, V, will be used as design parameters. Thus, the probability that a storm will produce a certain amount of precipitation, *p*, will be denoted as:

$$P[\Psi = p]$$

the probability that a storm will last a certain duration, t, will be denoted as:

$$P[\delta = t]$$

and the probability that a storm will produce a certain wind velocity, v, will be denoted as:

$$P[V = v]$$

where the wind velocity can be an average or maximum, depending on how the significant storm is characterized. The wind velocity of the storm in question is only used in storm surge analysis for the proposed framework.

Following the previous guidelines, an alternative probabilistic framework for describing riverine flooding due to a storm could be presented as:

$$\lambda(IM > x) \approx \sum_{i=1}^{N_s} \sum_{j=1}^{N_\Psi} \sum_{k=1}^{N_\delta} \lambda(\Psi_i > p_{min}) P[IM > x|p,t] P[\Psi = p] P[\delta = t]$$

This summation form is more reflective of the computational basis that is typically used to solve the hazard relationship. The variable *x* would be the flood level or water height. Similar variables have been defined in the preceding sections. The recurrence relationship, $\lambda(\Psi_i > p_{min})$ basically describes the rate at which storms with a minimum precipitation occur. A relationship for the recurrence relationship could be derived from data and simulations similar to what is shown in Figure 3, which shows exceedance and engineering parameters that can be considered.

Let us define P[IM > x | p, t] as a flood level prediction relationship, FLPR, similar to the attenuation relationship described earlier. In this case, the FLPR results in a water height as opposed to a river depth, thus incorporating local riverine topography. Figure 5 shows a hypothetical FLPR for a river due to a storm. As storm precipitation increases, the resultant flood height should also increase, however as a δ increases, the flood height should decrease. This is because at a constant Ψ, the precipitation intensity would lower as the δ increased. The figure shows FLPR contours based on duration, but the contours can easily be a function of another parameter. The FLPR should also account for drainage basin characteristics as well as riverine topography, such as bank slope or local irregularities.

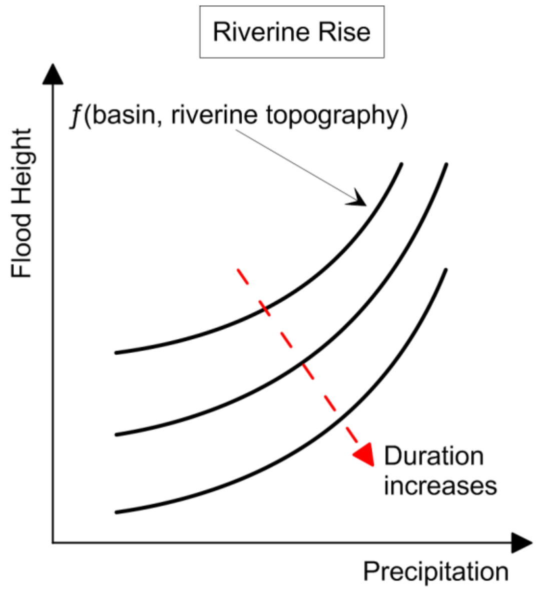

Fig. 5. Hypothetical flood level prediction relationship showing resultant flood height from storm precipitation and duration on a river.

A proposed probabilistic framework for describing storm runoff would also be similar to the relationship shown in the previous section on riverine flooding. The difference would come from the FLPR, with a hypothetical example show in in Figure 6.

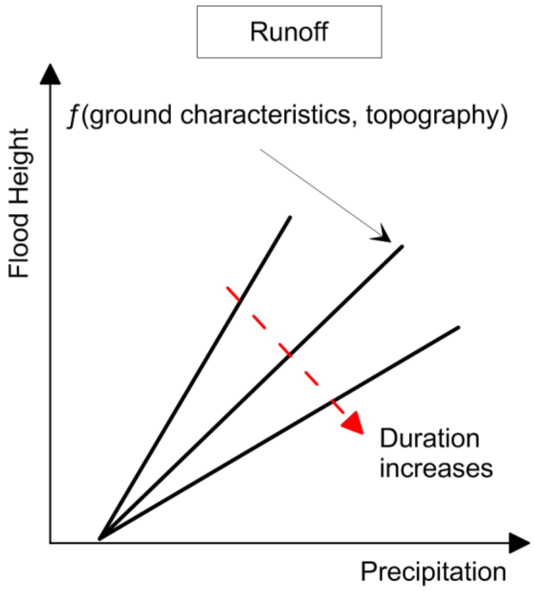

Fig. 6. Hypothetical flood level prediction relationship showing resultant flood height from storm precipitation and duration on ground, resulting in runoff.

Figure 6 shows a similar relationship to the proposed riverine FLPR, where an increase in precipitation results in an increase in flood height, while an increase in duration results in a decrease in flood height. The FLPR curves start away from the "origin" and are relatively more linear because runoff begins after the ground has absorbed a certain amount of water, represented by hydraulic conductivity, which should be encapsulated in the local function incorporating ground characteristics and topography.

As this is preliminary on top of spatial constraints, additional flooding mechanisms will not be addressed. However, an issue is the probability, or joint probability, of an earthquake occurring during the effects of a significant storm. The proposed framework considers them to be independent, although an investigation would likely be needed to ascertain this. Another issue is the cascading failure of multiple dams. Since dams outlet to the same riverine, one dam failure could lead to another dam failure. The proposed framework does not explicitly account for this, as independence of dam failures is implicitly integrated, but it is not outside the limits of converting the FLPE into an iterative process.

3. Conclusions

The paper attempts to propose a probabilistic flood hazard analysis framework. Although not every flood mechanism was considered, the ideas can be extended to account for other mechanisms. This framework can be useful in site evaluations and characterizations for nuclear power related sites, especially for radioactive waste disposal sites which are becoming a hot topic as nuclear power plants are aging and long-term storage options have multiple hurdles. The flood mechanisms considered were riverine, runoff, dam breaches from precipitation and seismic events, and storm surges. The recurrence relation is converted to a precipitation event, while for dam breach due to an earthquake the relation remained the same, outlining the importance of flood mechanism. Additionally, several flood level prediction equations were offered in an abstract sense, considering flooding behavior and site parameters. The proposed probabilistic flood hazard analysis framework does not consider joint events, such as a simultaneous storm and earthquake, as well as multiple upstream dam failures.

ACKNOWLEDGEMENT

This work was supported by the 2019 Research Fund of the KEPCO International Nuclear Graduate School (KINGS), Republic of Korea.

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