Analysis of Flood-Induced Nuclear Accident Propagation Mechanisms Using System Dynamics

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1. Introduction

Increasing risks of extreme rainfall and flooding have become important considerations for the safety of critical infrastructure, including nuclear power plants [1]. External flooding may cause not only inundation of structures and equipment but also loss of electrical power, degradation of cooling functions, and delays in emergency response and recovery [1,2]. These factors can interact over time and contribute to further accident progression. Therefore, the dynamic relationships among flooding, power functionality, cooling capability, and emergency response need to be considered simultaneously [3]. In this study, a system dynamics (SD) model was developed to represent the propagation of a flood-induced accident from equipment-area inundation to power loss, cooling-function degradation, and increasing accident risk. Flood detection, decision making, drainage, power recovery, and emergency power deployment were also incorporated to represent the interaction between accident progression and response activities.

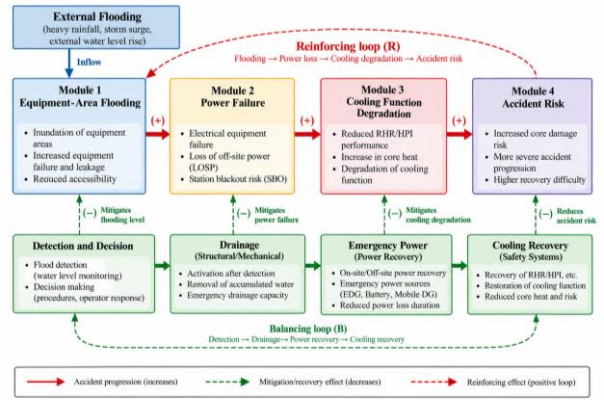


Fig. 1. Conceptual structure of the SD-based flood-induced nuclear accident propagation model.

2. Methods and Results

An SD-based accident propagation model was developed to analyze the temporal progression and response processes of flood-induced events. System dynamics has also been applied to nuclear safety problems to represent interactions among multiple factors and changes in system conditions over time [4]. The model consists of four major modules representing equipment-area flooding, power functionality, cooling-function degradation, and accident risk. These modules were dynamically linked to represent both the propagation of system degradation following flooding and the mitigation effects of drainage, recovery activities, and emergency power deployment.

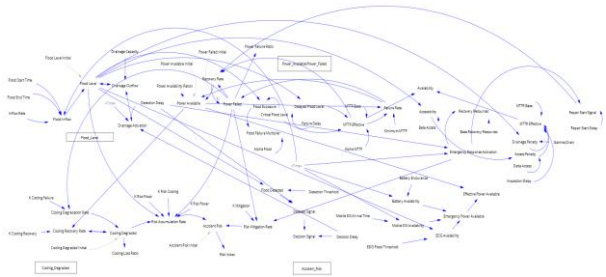


Fig. 2. Stock-and-flow diagram of the developed SD model.

2.1 Equipment-Area Flooding

The flooding module represents temporal changes in inundation within equipment areas according to external flood inflow and drainage. Meteorological and hydrological hazards, including flooding, are recognized as important external hazards in the safety assessment of nuclear installations [1]. Flood conditions can be represented using external flooding or water entering the target building, allowing future integration with time-series results obtained from two- or three-dimensional flood simulations. Hydraulic and hydrological analyses have been applied to evaluate temporal changes in inundation and drainage conditions at nuclear power plant sites [5]. Drainage is initiated after flood detection and operational decision making rather than immediately after inundation begins. This structure enables the model to represent changes in flood duration and severity associated with delays in emergency response.

2.2 Power Failure and Recovery

The power module represents the transition of electrical systems from an available state to a failed state under flooding and their subsequent recovery. The Fukushima Dai-ichi accident demonstrated that tsunami-induced flooding of emergency diesel generators and associated electrical equipment can

result in extensive loss of electrical power [2]. The likelihood of power failure therefore increases as inundation becomes more severe, while a delay between flood exposure and actual functional failure is also considered. Recovery includes not only equipment repair but also site accessibility, drainage conditions, inspection, and preparation for restoration activities. Consequently, flooding affects both the occurrence of electrical failures and the time required to restore power functionality.

2.3 Cooling Function Degradation

The cooling module represents the degradation of cooling capability during prolonged power loss and its recovery when electrical power or alternative power sources become available. Experience from the Fukushima Dai-ichi accident demonstrated that prolonged loss of electrical power can significantly affect the ability to maintain decay heat removal and cooling functions [2]. Cooling degradation was therefore introduced as an intermediate system state between power failure and overall accident escalation. This structure allows power loss to influence accident progression through deterioration of cooling capability rather than being treated directly as the final accident condition. It also enables the effects of power restoration and emergency power availability on maintaining and recovering cooling functions to be evaluated.

2.4 Accident Risk and Emergency Response

The accident-risk module represents the combined effects of flooding, power loss, and cooling degradation on accident progression over time. Accident risk is treated as a relative indicator of system deterioration rather than an absolute probability of a specific nuclear accident. Dynamic safety assessment approaches emphasize the importance of considering temporal interactions among plant conditions, component states, and response actions during accident progression [3].

Emergency-response processes include delays associated with flood detection, field confirmation, reporting, and decision making, followed by drainage and recovery actions. Batteries, emergency diesel generators, and mobile diesel generators are also considered as alternative power sources that can mitigate cooling degradation following power loss. The importance of alternative and emergency power sources during extended loss-of-power conditions has been emphasized following the Fukushima Dai-ichi accident [2]. The developed model represents a reinforcing accident-propagation process in which increasing flooding leads to power failure, cooling degradation, and higher accident risk, while drainage, power recovery, and emergency power deployment provide balancing mechanisms that mitigate further accident progression.

3. Conclusions

An SD-based model was developed to represent the propagation of flood-induced nuclear power plant accidents from equipment-area inundation to power loss, cooling-function degradation, and increasing accident risk. The model dynamically links flooding with changes in electrical and cooling functionality and incorporates emergency-response factors including flood detection, decision making, drainage, recovery, and emergency power deployment. The developed framework can therefore represent the effects of flooding on both equipment failure and subsequent response and restoration processes. Future work will integrate external and internal flood simulation results and equipment-specific failure and recovery information and will examine the effects of key response conditions through sensitivity analyses. The proposed framework can provide a basis for dynamically evaluating major factors affecting the progression and mitigation of flood-induced nuclear accidents.

ACKNOWLEDGMENT

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