

Analysis of an Optimization-Based Reinforcement Effect Assessment for Flood Fragility Structures in NPPs

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1. Introduction

Recent climate change has increased the frequency and intensity of extreme rainfall events and associated hazards, elevating flood risk at nuclear power plant (NPP) sites. Flood-induced failure of safety-related structures can significantly degrade plant safety margins. Therefore, a rational reassessment of design criteria and a quantitative evaluation of reinforcement effectiveness are essential to ensure long-term flood safety.

Among flood fragility structures, the Essential Service Water (ESW) Intake Structure plays a critical role in maintaining the capability to remove heat. In this study, an optimization-based framework is developed to (1) reassess the design threshold height (h) under probabilistic flood conditions and (2) evaluate the improvement in structural performance resulting from reinforcement using fragility analysis.

2. Probabilistic Flood Assessment and Statistical Modeling

Flood depth data corresponding to multiple return periods were used as input for probabilistic flood assessment. To characterize the statistical behavior of flood depth, three candidate probability distributions were considered:

- ✓ Lognormal distribution
- ✓ Gamma distribution
- ✓ Weibull distribution

The most appropriate distribution was selected using the Akaike Information Criterion (AIC)

Based on the selected distribution, more than 10,000 Monte Carlo simulations were performed to generate stochastic flood depth samples. Flood occurrence was defined as:

$$\text{Failure} = \begin{cases} 1 & \text{if } d > h \\ 0 & \text{otherwise} \end{cases}$$

where d is the simulated flood depth, and h is the design threshold height.

The flood probability was estimated from simulation results, and the upper bound of the 95% confidence

interval was calculated. The safety constraint was defined.

3. Optimization-Based Determination of Design Threshold Height

A Grid Search method was adopted because the flood probability decreased monotonically with increasing threshold height. The search interval was defined with a resolution of 0.01 m to ensure adequate precision while maintaining computational efficiency.

The optimization results indicate that the required threshold height increases with return period. Representative results are:

- ✓ 10,000 years → 0.41 m
- ✓ 100,000 years → 0.50 m
- ✓ 1,000,000 years → 0.55 m

The figure illustrates the rapid decrease in flood probability beyond a critical threshold, demonstrating the existence of a well-defined optimal solution satisfying the safety constraint.

4. Fragility analysis and reinforcement

4.1 Existing Design Condition ($h = 0.41$ m)

Under the current design threshold height of 0.41 m, fragility curves were derived and corresponding HCLPF values were obtained.

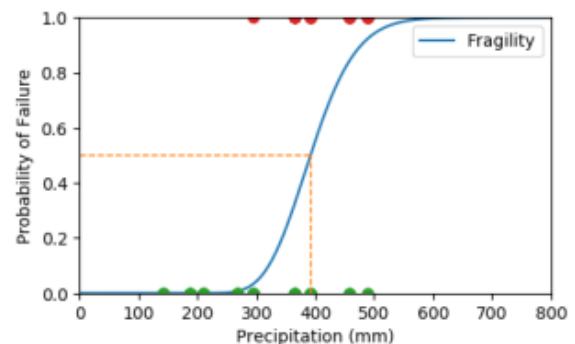


Fig. 1 Fragility curve under existing design (1)

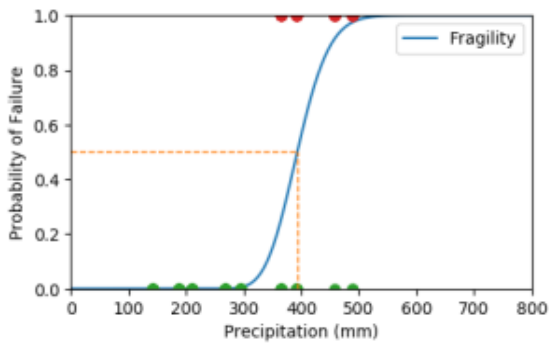


Fig. 2 Fragility curve under existing design (2)

2.2 Reinforcement Scenarios

Four reinforcement scenarios were considered:

- ✓ $h = 0.47$ m
- ✓ $h = 0.50$ m
- ✓ $h = 0.52$ m
- ✓ $h = 0.55$ m

Fragility curves were recalculated for each scenario.

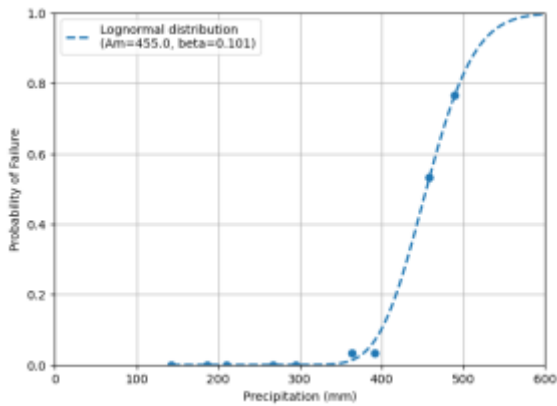


Fig. 3 Fragility Curve ($h=0.47$ m)

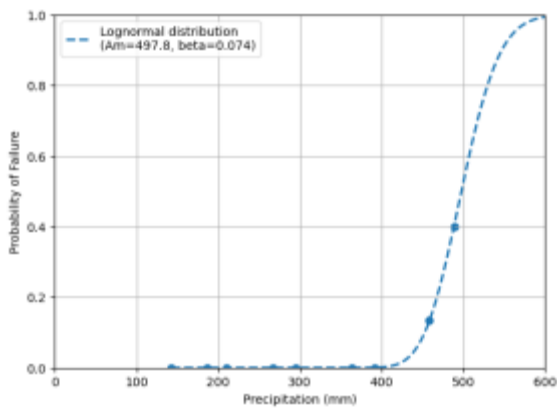


Fig. 4 Fragility Curve ($h=0.50$ m)

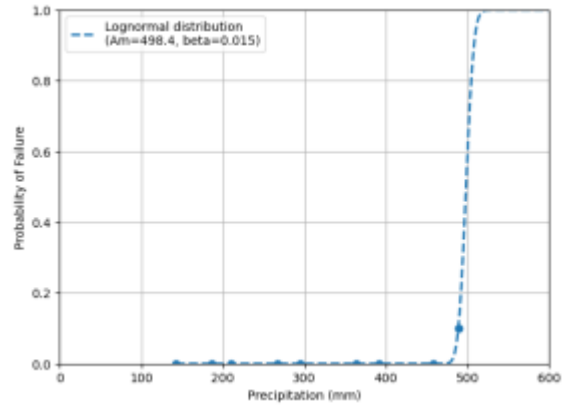


Fig. 5 Fragility Curve ($h=0.52$ m)

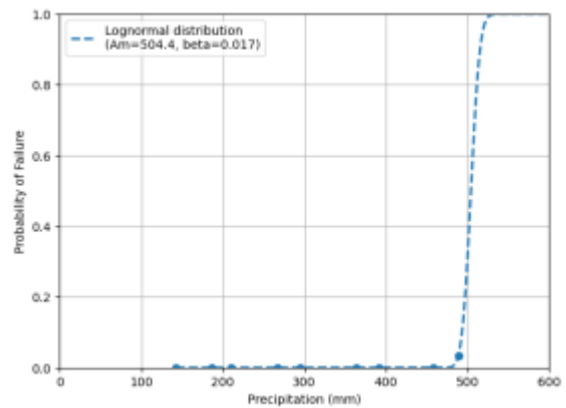


Fig. 6 Fragility Curve ($h=0.55$ m)

The rightward shift of fragility curves clearly indicates improved resistance against extreme precipitation.

5. Quantitative Evaluation of Flood Safety Improvement

The increase in HCLPF and corresponding performance improvement rates are summarized below.

Table. 1 Improvement in HCLPF and performance enhancement rate

| Threshold h (m) | HCLPF (mm) | Increase (mm) | Improvement (%) |
|-------------------|------------|---------------|-----------------|
| 0.47 | 359.6 | 56.3 | 18.6% |
| 0.50 | 419.3 | 116.0 | 38.3% |
| 0.52 | 481.2 | 177.9 | 58.7% |
| 0.55 | 484.8 | 181.5 | 59.8% |

The results demonstrate that reinforcement beyond 0.50 m significantly enhances safety margins. Notably, improvement increases rapidly up to 0.52 m and then saturates, suggesting diminishing marginal benefit beyond a certain level.

6. Conclusions

An optimization-based methodology was developed to reassess the design threshold height of flood-vulnerable structures in NPPs under probabilistic flood conditions. The minimum threshold height satisfying a 5% flood probability constraint at 95% confidence was determined using Monte Carlo simulation and Grid Search.

Subsequent fragility analysis demonstrated that structural reinforcement significantly enhances flood resistance performance, particularly beyond 0.50 m threshold height. The results provide a quantitative technical basis for rational design upgrades and long-term flood safety enhancement under increasing extreme precipitation conditions.

Acknowledgments

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