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ESTIMATING RISK FROM EVENT FREQUENCY AND LOSS OF FUNCTIONALITY

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ABSTRACT

The new ASME Plant Systems Design (PSD) code [Hill et al. 2022] aims to ensure that industrial facilities meet both safety and production targets through an iterative, risk-informed design process. This paper presents a methodology to estimate risk based on the frequency of hazardous events and the probability of loss of functionality caused by those events. The risk is quantified by integrating hazard and fragility curves, which respectively represent the frequency of events and the conditional probability of failure. A practical example involving the design of a sea wall is used to demonstrate this approach. Various design options are compared using cost-benefit analysis, combining construction costs, risk values, and potential failure costs. The methodology provides a structured basis for selecting optimum designs.

INTRODUCTION

The ASME Section III Plant Systems Design (PSD) Standards Committee is developing a technology - neutral standard for design of facilities with the potential for significant hazards to the health and safety of the public, the worker and the protection of the environment as described by Hill et al. (2022). The first activity is to conduct plant process hazard evaluations and analysis in the early stages of the design which advance as the design matures and provide structure to the development of a quantitative risk assessment. Pellereau et al. (2022) has explained that the new PSD standard includes requirements and guidance for design organisations to incorporate risk informed probabilistic design methodologies with traditional deterministic design methods using reliability and availability targets and has clarified use of Probabilistic Design Methods (PDM) at each of the three stages of conceptual, preliminary and final design. The purpose is to ensure that the facility design meets the safety and production targets. It will require an iterative process where the design is assessed to estimate risk from events that may lead to loss of functionality. Through an example, this paper presents a method to select an optimum design by computing risk from frequency of event and probability of loss of functionality caused by that event.

For a given design RISK (R) has two components:

HAZARD (H) which is the probability of hazard of different intensity ‘a’. It gives likelihood of an undesirable event occurring.

FRAGILITY (Pf) is the likelihood of loss of functionality/failure happening under given intensity ‘a’ of the hazard.

The RISK (R) is given by:

$$\text{RISK (R)} = \text{HAZARD (H)} * \text{FRAGILITY (Pf)} \quad (1)$$

An example is presented to demonstrate how a hazard curve can be integrated with a fragility curve to obtain risk of loss of functionality/failure. If the intensity of a hazard is taken as 'a' which varies from 0 to 1 then H and Pf can be represented as functions of 'a' as shown in Figs 1 and 2. Here the intensity 'a' can represent the load/demand generated by the hazard. Note that it is not practically possible to reduce a hazard to nil but for engineering purposes it can be reduced down to frequency of 10^{-5} to 10^{-6} or even lower if required.

HAZARD

The typical hazard curve is frequency vs magnitude of hazard is often represented as a log-normal distribution. This means that smaller events occur more frequently, while larger events become increasingly rare. If the intensity of a hazard is taken as 'a', its annual probability of occurrence, H(a) is shown in Fig 1. As can be seen from Fig 1, extreme events where hazard can cause high load/ demand have a very low frequency of occurrence. In log-log scale, the hazard curve is almost a linear function. These events leading to loss of functionality / failure can be due to external or internal hazards like earthquake, flood level during tsunami, over pressure caused by ballast, unplanned equipment failure, chemical spills, accidents etc.

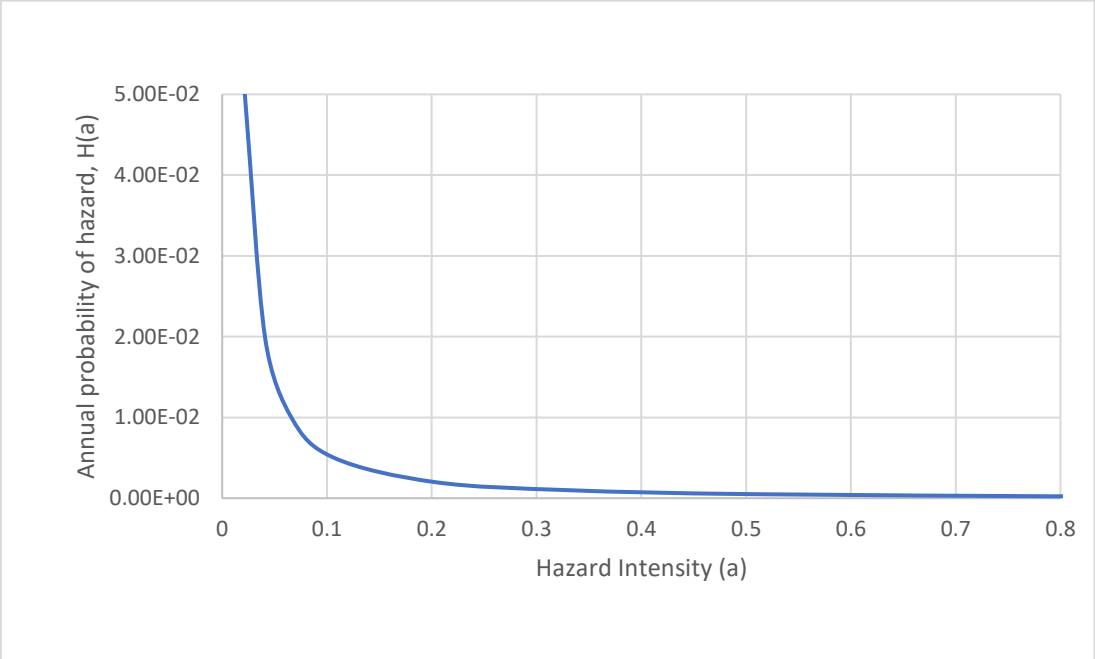

Figure 1. Hazard curve showing annual probability vs intensity of hazard

FRAGILITY - CONDITIONAL FREQUENCY OF FAILURE

Fragility is the conditional frequency of failure given a value of the load/demand such as stress, moment, acceleration etc caused by the hazard.

Typically, probability of failure (Pf) at load/demand 'L' created by H for nonexceedance probability level Q is given by:-

$$Pf\,|_L = 1 - \left[\Phi\left(\frac{\ln(L/Sm) + \beta_u\,\Phi^{-1}(Q)}{\beta_r}\right)\right] \quad (2)$$

where Q is the confidence level. Φ is the Gaussian cumulative function and Φ^{-1} is the inverse of Φ.
Capacity or Strength (S) = Sm x ε_R x ε_U
Sm = Median strength
ε_R = Random variable (unit median) representing inherent randomness in S
ε_U = Random variable (unit median) representing uncertainty in S
ε_R and ε_U are lognormally distributed (with unit median) and have β_r and β_U as logarithmic standard deviations.

There are several methods of obtaining fragility curves. For structures, Probabilistic Design Methods (PDM) like the First Order Reliability Method (FORM) can be applied to predict probability of failure at a given load. Prinja and Ogunbadejo (2015) had used FORM to predict probability of failure of reinforced concrete containments subjected to over pressure.

A typical fragility curve is shown in Fig 2. A fragility curve has a sigmoidal (S-shaped) form. This curve represents the conditional probability of failure of a system, structure, or component (SSC) given different levels of load or demand where the probability of loss of function / failure goes from no failure (Pf=0) at negligible load/demand to failure (Pf=1) at high load/demand.

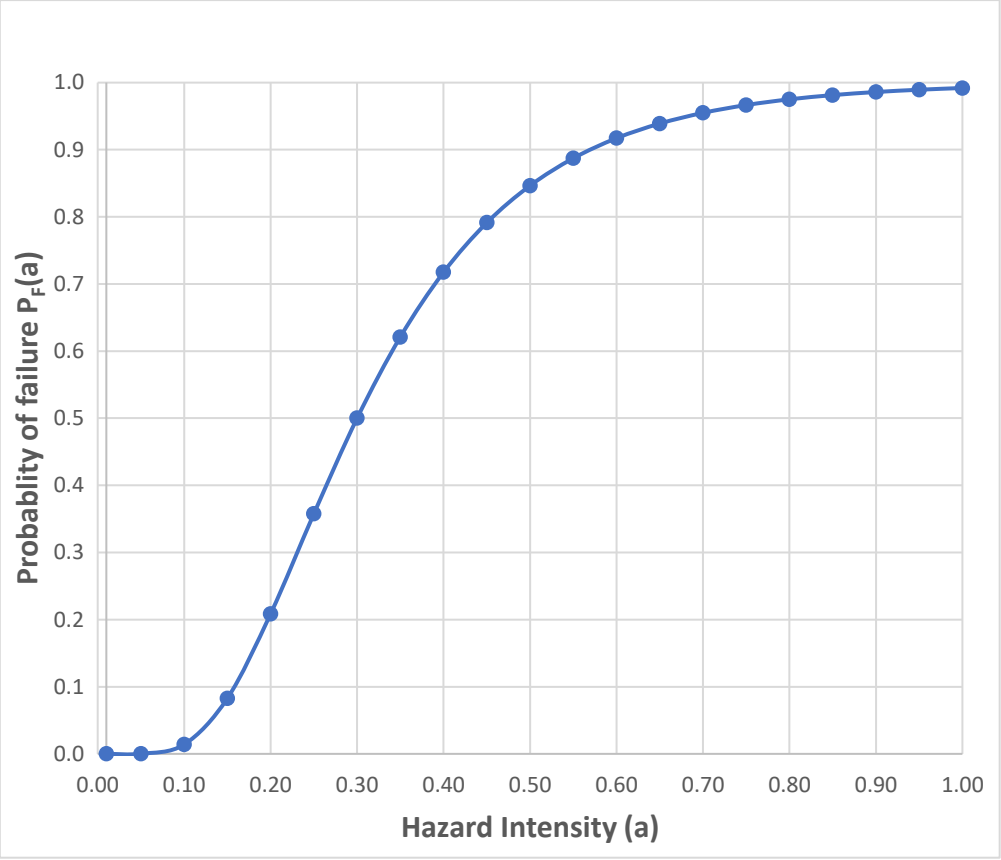

Figure 2. Probability of failure vs intensity of hazard

RISK

Hazard curve H(a) and fragility curve Pf(a) given as function of hazard intensity (a) can be combined to obtain risk R by numerical convolution by either of the two equations:-

$$R = -\int_{0}^{+\infty} P_F(a)\left\{\frac{dH(a)}{da}\right\}da \tag{3}$$

Or

$$R = \int_{0}^{+\infty} H\,(a)\left\{\frac{dP_F(a)}{da}\right\}da \tag{4}$$

Risk 'R' is obtained by multiplying the probability of failure by rate of change of hazard magnitude in equation (3) or by multiply the hazard magnitude with the rate of change in probability of failure in equation (4) integrated over the whole range of possibilities. Risk 'R' will be same from both equations. Negative sign is used in equation (3) because of the negative slope of the hazard curve. These equations can be solved numerically. With some simplifications, the integration can be done for seismic hazard as shown by Kennedy (2007). Typical hazard curves are close to linear in log-log scale and can be approximated by a power law:

$$H(a) = Ka^{-K_H} \tag{5}$$

K is constant and K_H is slope parameter. K known as Structural Scale Factor is calculated using the above equation with H set to reference exceedance frequency Href. In this case, H = Href = $1x10^{-4}$ i.e. annual probability of hazard exceeding reference intensity 'aref' is $1x10^{-4}$.

If θ is the mean and β is the logarithmic standard deviation of the fragility. Taking M=ln θ and x=ln(a), risk (R) can be calculated from:-

$$R = \frac{K}{\beta\sqrt{2\pi}}\int_{0}^{+\infty}\left[exp\left[K_H\,.\,x - \left\{\frac{(x-M)^2}{2\beta^2}\right\}\right]\right]da \tag{6}$$

In this example, the integration of the hazard curve (Fig 1) with the fragility curve (Fig 2) using the above equation yields: R = 8.4 x 10^{-7}.

This risk 'R' can be calculated for any of the following external and internal hazards for an industrial plant provided their hazard curve and fragility curve are known.

TYPES OF HAZARDS

Designing an industrial plant requires careful consideration of both external and internal hazards to ensure safety and operational efficiency. Here is a list of these hazards:

External Hazards

Seismic Events: Earthquakes and related ground movements.
Meteorological Hazards: Extreme weather conditions such as hurricanes, tornadoes, heavy rainfall, snowstorms, and lightning.
Hydrological Hazards: Flooding, tsunamis, and storm surges.
Geological Hazards: Landslides, soil erosion, and volcanic activity.
Biological Phenomena: Infestations by pests or invasive species.
External Fires: Wildfires or fires originating outside the plant.
Accidental Aircraft Crash: Impact from aircraft accidents.
Transportation Accidents: Hazards from nearby road, rail, or maritime transport accidents.
Industrial Accidents: Incidents at nearby industrial facilities.
Electrical Disturbances: Power outages, surges, and electromagnetic interference.
Human-Induced Hazards: Acts of terrorism, sabotage, or other malicious activities.

Internal Hazards

Internal Fires: Fires originating within the plant due to equipment failure, electrical faults, or human error.
Internal Explosions: Explosions caused by chemical reactions, gas leaks, or pressure vessel failures.
Internal Missiles: Projectiles generated by equipment failure or explosions.
Pipe Breaks: Pipe whip, jet effects, and flooding due to pipe ruptures.
Internal Flooding: Flooding caused by internal leaks or failures in water systems.
Heavy Load Drops: Hazards from the accidental dropping of heavy equipment or materials.
Chemical Spills: Release of hazardous chemicals due to leaks or spills.
Radiation Hazards: Exposure to ionizing radiation from equipment or materials.
Mechanical Failures: Failures of machinery or structural components.
Human Error: Mistakes made by personnel during operation or maintenance.

These hazards must be identified, assessed, and mitigated through robust design, safety measures, and emergency response plans to ensure the safe operation of the industrial plant. The following procedure can be used to perform risk assessment and achieve the design target.

RISK ASSESSMENT USING HAZARD AND FRAGILITY CURVES

Risk Estimation

Risk is estimated by combining the hazard and fragility curves across all possible hazard levels.

Cost Estimation

For each design, three main costs are calculated:

i. Construction Cost: This is what it takes to build the structure. This will include material cost, labour cost and other costs related with permits and licensing etc.

ii. Maintenance Cost: Costs for upkeep over its lifetime.
iii. Failure Cost: If the structure fails, this covers economic losses, repairs, or any harm caused.

Selecting the Best Design

The best design is selected by performing cost benefit analysis as follows:
Calculate the Total Cost (C) = construction cost + maintenance cost
Calculate benefit = Failure cost (V) x Risk (R)
Select the design that has the lowest Benefit / Total Cost ratio.

The calculated risk 'R' for each of the hazards can be used to identify the dominant risks and can help to identify the optimum design option if several designs are proposed for protection against a hazard. For ease of comparison, risk 'R' can be multiplied by Failure Cost (related with asset value) 'V' to obtain Benefit 'B'.

$$B = V \times R \tag{7}$$

A simple table can be created to help with risk assessment and target setting as shown in Table 1.

Table 1. Risk assessment of hazards

Hazard (i)	Risk (Ri)	Cost (Ci)	Benefit (Bi)
1	R1	C1	B1
2	R2	C2	B2
3	R3	C3	B3
4	R4	C4	B4

If the risk 'R' or the cost of failure 'C' arising from any hazard is not acceptable, design must be iterated. It will be judicious to identify the hazard that contributes most to the risk 'R' or the cost 'C' and identify the events that are dominant in that hazard. Engineering measures for these unacceptable events can be taken to reduce their impact and bring them within the acceptable limits paying attention to the construction and maintenance costs. Risk can be lowered by taking measures to lower the hazard frequency or the design can be changed to improve fragility or both can be tried to reach the acceptable target design as shown in Fig 3. When designing a System, Structure or Component (SSC) against an extreme event that has low probability of occurrence but very high load or demand, it is prudent to take the above approach and design to achieve a target reliability. Note that in case of an external hazard like seismic or tsunami, it is not possible to reduce the frequency of hazard at a given site, so emphasis is mostly on design iteration.

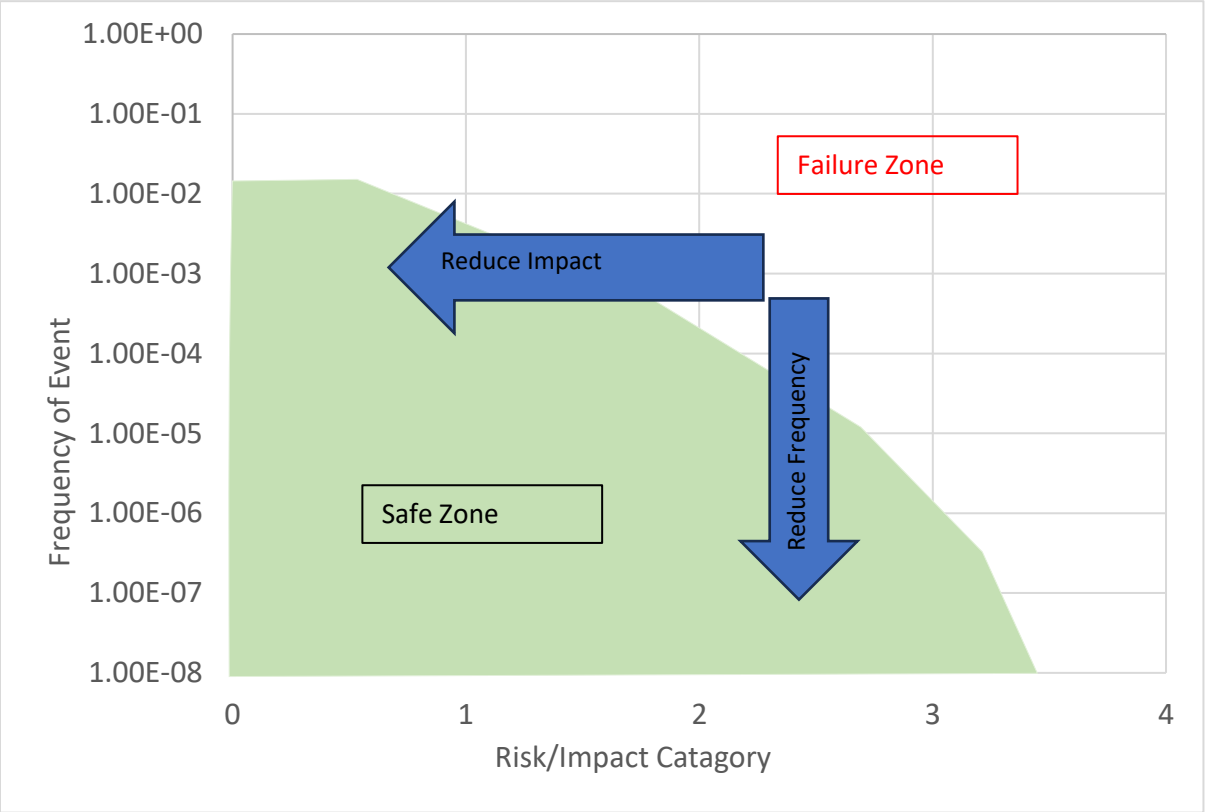

Figure 3. Design options to reduce risk

EXAMPLE: DESIGN OF SEA WALL

In this example we consider selection of a design of a sea wall to protect a critical structure against tsunami hazard. Here the Failure Cost (V) is assumed to be $1x10^9$ dollars. The total cost of building a seawall depends on the dimensions, material costs, labour costs, and extra expenses. Here's the step-by-step calculation process:

Calculate Seawall Volume (Vol) to estimate the amount of material needed from the given wall length (L), height (H) and average width (W):

$$Vol = L \times H \times W \tag{8}$$

Material Cost (Cm) is given by: $Cm = Cunit \times Vol$ (9)
Where Cunit is Cost per cubic unit.

Labour cost (CL) is calculated based on labour cost per unit length (Cper): $CL = Cper \times L$ (10)

The final Total Cost (C) is calculated as:

$$C = Cm + CL + Cextra \tag{11}$$

Where Cextra is any additional costs related with maintenance, permits and site preparation etc which in this case are assumed to be constant for all different designs of the sea wall and therefore, taken out of the cost comparison. The Material Cost (Cm) is taken as $196 per cubic meter and labour cost (CL) is taken as $164 per linear meter. The total cost (C) based on the design parameters (L, H and W) for each of the four designs is given in Table 2.

Table 2. Cost comparison of different designs of sea wall

Design	Length (m)	Height (m)	Width (m)	Total Cost, C ($)
1	500	2.0	1	278000
2	500	3.0	0.5	229000.
3	500	3.5	1	425000
4	500	4.0	1	474000

The tsunami hazard curve given as flood level (m) vs annual probability is given in Fig 4. There are four designs of a sea wall being considered with varying costs. Aim is to design a sea wall that can provide protection against 2m of flood level. The fragility curves of these designs are given in Fig 5. Summary of the risk calculated using the above procedure is presented in Table 3. Note that the risk (R) estimated from both equations 3 and 4 are the same.

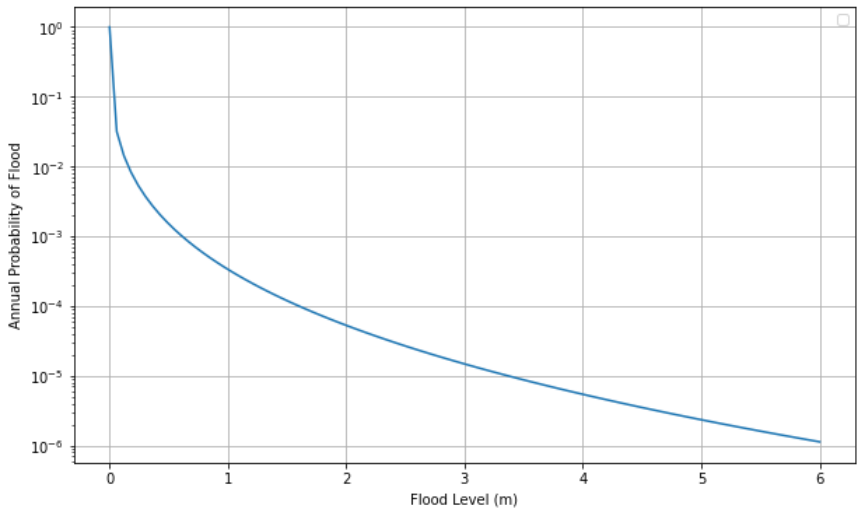

Figure 4. Hazard curve for flood levels considered for sea wall

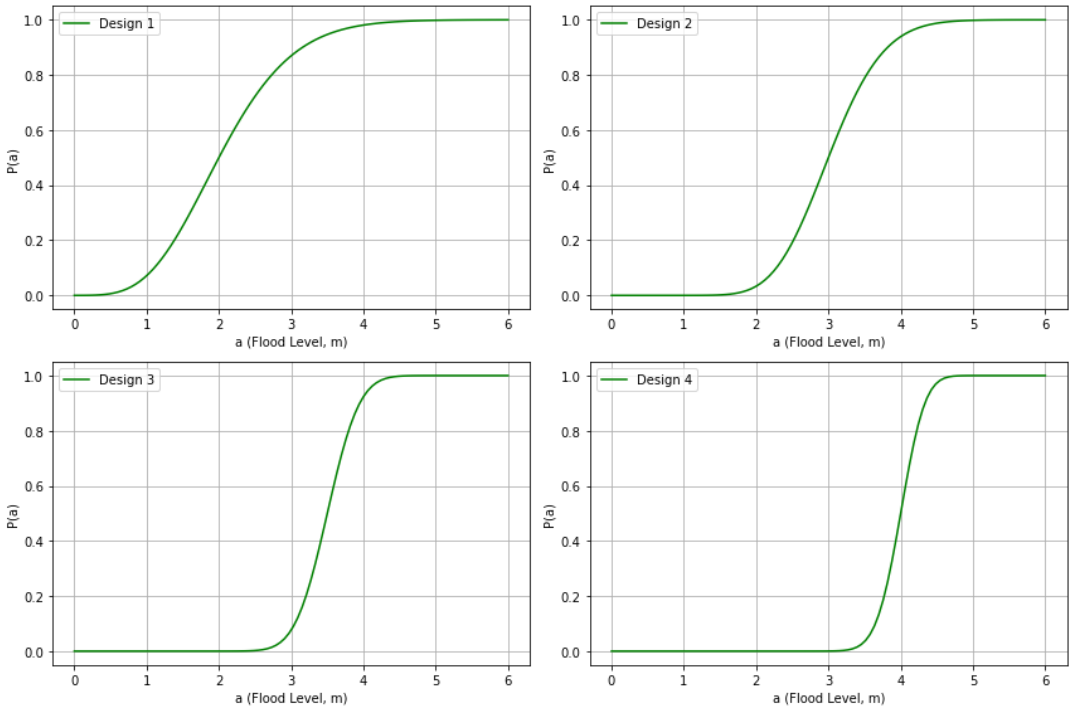

Figure 5. Fragility plots for the various sea wall designs

Table 3. Risk Computation Results

Design	Height	Risk (dH/da x P)	Risk (dP/da x H)	Cost Benefit Ratio (B/C)
1	2.0	0.00012670	0.00012641	4.55
2	3.0	0.00001885	0.00001885	0.82
3	3.5	0.00000941	0.00000941	0.22
4	4.0	0.00000564	0.00000564	0.12

CONCLUSIONS

This paper demonstrates a quantitative method for estimating risk by integrating hazard frequency with fragility of failure, facilitating risk-informed decision-making in structural design. Using an example of a sea wall subjected to tsunami hazards, four design options were evaluated based on their risk and cost-benefit ratios. The best design is Design 1 with the highest cost-benefit ratio of 4.55 that has the lowest total cost ($278,000) compared to the other designs. Despite having a higher risk value (0.00012641), the cost-benefit ratio indicates that the benefits of risk reduction relative to the cost are significantly higher. Therefore, Design 1 strikes a balance between construction costs and risk reduction, making it the most economically viable option.

The key conclusions are:

Risk Estimation: The integration of hazard and fragility curves provides a robust measure of risk when designing against hazards some of which can include extreme events.

Design Evaluation: Among the four sea wall designs, Design 1 showed the highest cost-benefit ratio despite having a higher calculated risk. This suggests that in some cases, a lower-cost design may offer the most favourable economic trade-off if the increase in risk remains within acceptable limits.

Iterative Optimisation: The proposed method supports iterative design refinement by identifying dominant hazards and evaluating their individual contribution to overall risk and cost.

Application of ASME PSD Code: The methodology aligns with the objectives of the new ASME PSD code, providing practical guidance for integrating probabilistic risk assessment into engineering design.

Overall, the approach presented enables informed selection of design alternatives by quantifying and comparing risk and cost, thereby supporting the development of safe, efficient, and economically justified industrial systems.

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