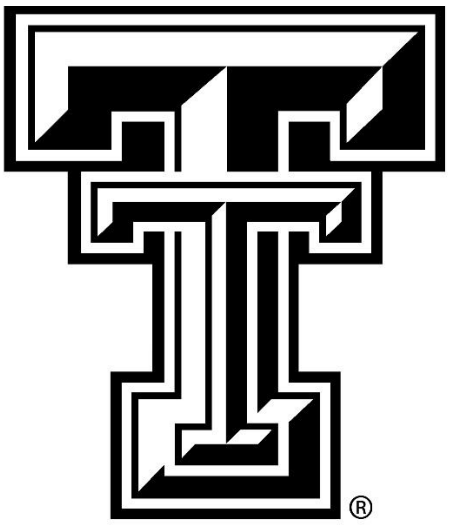

Probabilistic approach in Water Resources Engineering
ME 5352 Probabilistic Design
Submitted To: Dr. Ekwaro

PROJECT I

Abstract

The paper briefly discusses on deterministic and probabilistic approach of design and highlights the increasing supersedence of deterministic approach in recent years. Further, the paper explores some commonly used approaches in probabilistic design, often used software tools and wide spread application of probabilistic approach. Despite of high safety and reliable design approach, the probabilistic approach do have some limitations in design process and is discussed in the last section of report.

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"Probabilistic approach in Water Resources Engineering: Increasing supersedence of Deterministic approach while acknowledging the fundamentals of Deterministic design."

Abstract

Engineering design is often associated with uncertainties. The uncertainties could be either due to the measurement errors or natural inherent uncertainties, and it has always been a challenging task for engineers to come up with better judgements and estimates. Several human activities and the changing climate has led to non-stationarity in the system. Because of which, the classical approach of deterministic design and stationarity has some limitations. The deterministic approach accounts for uncertainties through the introduction of Factor of Safety, and is always the base for probabilistic approach. However, it has likely chances of throwing away the data which is useful in risk assessment and decision-making process. The modern engineering design mostly deals with random variables rather than a deterministic value regarding dynamic system. In probabilistic design, the variables are treated as a random variable and is represented by probability distributions. Thus, it considers the uncertainties associated with the variable. The content briefly discusses the introduction of probabilistic design over classical approach, it's advantages and application, commonly practiced approaches and the techniques. In addition, it aims to highlight some limitations and the complications in using this approach.

Keywords: ***random variable, probability, deterministic design, probabilistic design***

Introduction

The deterministic approach was widely used among engineers in design and analysis before the introduction of probabilistic approach. This approach was based on stationarity where the factor of safety is determined from past knowledge and experience. Deterministic approach does not make any consideration for prediction of flow of variability in the system. In simpler words, no randomness is involved in the development of future states of the system [2]. Also, there is no information on how the variables of the system affect the safety thus this approach is not as good in guaranteeing the performance or safety of the system. Safety factor being a deterministic value, do not provide suffice information to achieve the best use of resources. There are chances of going through over design or under design using the safety factor as a basis and may possibly lead to uneconomical or unsafe design. As a matter of fact, there has been increasing concerns about the safe and economical design using the probabilistic approach [1].

Several design guidelines have been recently revised to incorporate the probabilistic analysis. The American Institute of Steel Construction Load and Resistance Factor Design, and the European and Canadian structural designs have been revised. The revisions in the code are expected to provide more information about the system behavior, influence on different variables on the performance, and interaction between several components of the system. With the increasing concerns about reliability and probabilistic approach, many schools now include the concepts of probabilistic design in the curriculum realizing its importance in engineering. While considering the uncertainty in the design process,

probabilistic design does not discount the experience or expertise gathered from a system. In fact, it includes a 'professional factor' which incorporates the expert opinions of experienced engineers [1].

Probabilistic design is an engineering design which primarily deals with the consideration of the effects of random variability upon the performance of an engineering system during the design phase. It is different from deterministic approach in terms of assuming a small probability of failure instead of using the safety factor. In probabilistic approach, each variable can have multiple values and the exact value cannot be predicted. However, we can define the chance or probability that the given random variable may take a certain range of values. The goal of this approach is to get a design that will best represent the situation and yields an enriched information on decision making, while exhibiting the smallest effects of random variability [2].

With the advancement in probabilistic approach, we can have better information required for optimum design. This approach helps in advancing the design and safety by maintaining a sound balance between minimizing cost and maximizing safety levels. It has been very effective in terms of reducing the need for models or prototypes, reduction of failure cost and avoids material wastage. In addition, it has led to increased assurance in analysis and improvements in reliability of the design [2].

The two approaches are not completely independent, however the way in which the prediction is done varies between these approaches. Deterministic approach assumes straightforward cause and effect: the same cause, with the same force, yields the same effect at the same magnitude. The probabilistic model, also called the stochastic model, assumes that the same cause may produce different effects each time, and yields a range of effects produced by the same cause [3].

To summarize in simple words, the probabilistic approach differs from the deterministic approach by incorporating uncertainty into the system. The deterministic approach never talks about the risk and reliability and the design is based on deterministic value, where there are maximum chances of throwing away useful information to get that single value. On the other hand, probabilistic approach deals with random variable and talks about the risk and reliability. This approach enriches the information and helps in decision making as compared to traditional approach. Furthermore, results obtained from deterministic approach is a single value with units as the input value, which is compared against a safety factor and decision is entirely based on that single value. Whereas, probabilistic approach gives a probability and is compared against probability of failure. Having said this, does not imply that the two approaches are completely independent, and one is better over the other. Both have their own significance under different scenarios. A recent paper by R. Gabe Merrill et al. describes an approach used by the NASA Constellation Program Strategic Analysis Team (SAT) to integrate deterministic and probabilistic analysis of human lunar exploration scenario options. Good candidates for implementation were selected from many scenario options using deterministic analysis which was less computationally, and time-intensive and probabilistic analysis was then used in evaluating expected performance and robustness [4]. This paper discusses the various probabilistic approaches and techniques, applications and limitations.

Probabilistic Design Methodology

Probabilistic Design Approaches

The main objective of this chapter is to highlight on some commonly used reliability analysis techniques. The basis of many probabilistic techniques is the limit state theory. These techniques are generally used to determine the limit state functions, also called the performance functions. The difference between resistance and the load on the system is defined as performance function in the simplest case, and is generally written in terms of displacement, strain, stress, etc. in reliability engineering. Based on structural conditions, performance function can be related as in Eq. (1) and Eq. (2). The integral of the joint probability function of the random variable over the complete failure region is used to determine the Probability of Failure (POF) given by Eq. (3) [5].

Response Surface Methodology (RSM)

Response Surface Method (RSM) is an approximate mathematical function for the limit state and assumes that the influence of the random input variables on random output parameters can be approximated. The basic idea of this method is to approximate the system response Y(x) by an explicit function of random variables, and to improve the approximation via iterations. The system response can be approximated as given in Eq. (39) [5].

First Order Reliability Method (FORM)

First Order Reliability Method (FORM) works well for linear problems as it is linearized about the point with the highest probability, also known as the Most Probable Point (MPP). However, due to the very fact, the desired accuracy may not be obtained in case of non-linear problems using FORM. The FORM technique is easy to use but fails to make use of the distributional information. The POF and reliability is estimated by equations, Eq. (7.1) and Eq. (7.2) respectively [6].

Second Order Reliability Method (SORM)

SORM provides more accurate results as compared to FORM, but is more computationally intensive. Unlike FORM, in SORM a parabolic surface is fit to the limit state function at MPP, thus improves the assessment given by FORM by including information about the curvature.

Variance Reduction Technique (VRT)

Variance Reduction Technique (VRT) is aimed at reducing the variance without disturbing the expected or mean value and without increasing the sample size. Despite the loss in basic simplicity, VRT increases the efficiency and accuracy of the risk or reliability estimation [1].

Simulation of Correlated Random Variables or Coupling Formula

Most of the above discussed techniques assumes that all random variables are uncorrelated. However, there are circumstances where we need to estimate POF for correlated random variables. In such case, Taylor expansion can be used to approximate variance of response using the variable's standard deviation and mean. The coupling formula can be then used to calculate standard normal variate and the POF can be determined using standard normal distribution function [1].

Advanced Mean Value (AMV)

Advance Mean Value(AMV) is significantly efficient as compared to MCS, as it greatly reduces the number of evaluations of performance function. AMV assumes that a Taylor series expansion exists at the mean values if the limit state function is smooth.

Monte Carlo Simulation (MCS)

Monte Carlo simulation is a powerful statistical analysis tool and widely used in both engineering and non-engineering fields. It is based on random sampling of the variable and number of iterative runs on computer. In practical situations, sometimes it is impossible to evaluate POF directly and in such cases, MCS can be very useful in evaluating the POF. However, it requires number of iterations for better accuracy and high reliability. This process can be time consuming and costly. The basic steps of MCS are shown in the algorithm below: [6]

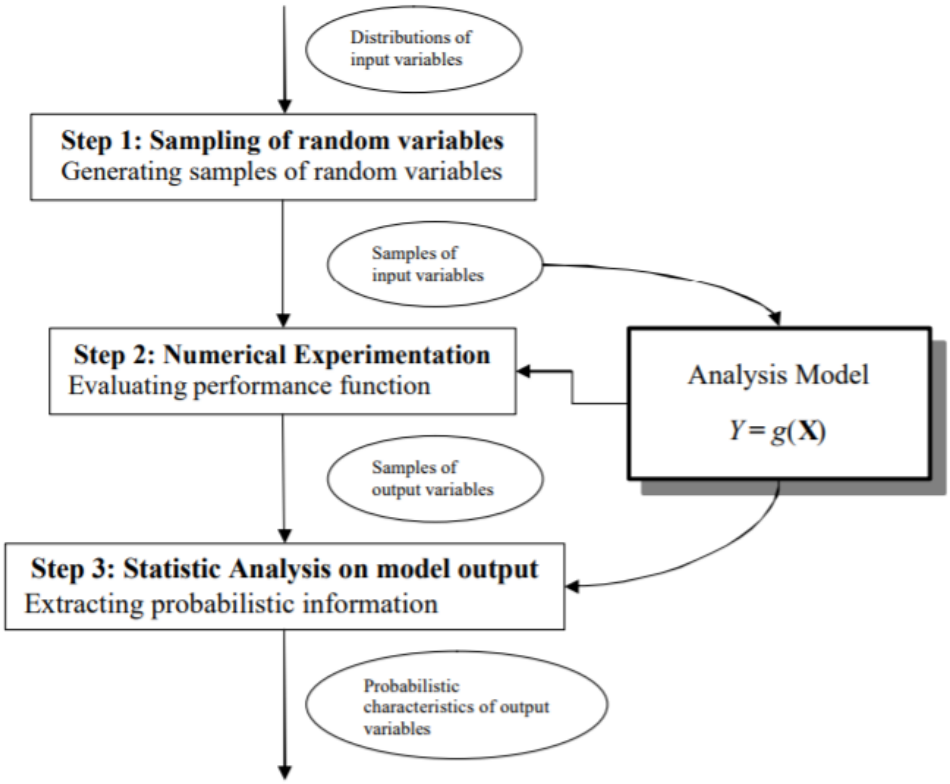

Fig 1: Steps in Monte Carlo Simulation

With several techniques available, there are criteria for evaluation. The efficiency and effectiveness of each technique can be compared over time required for analysis, cost incurred, and accuracy and robustness of model. There are several softwares available to aid in performing the techniques.

Probabilistic Design Software

RENO is powerful and user-friendly software designed for probabilistic event and risk analysis. It is a powerful and user-friendly platform for building and running complex analysis using an intuitive flowchart modeling approach and simulation [7].

Weibull++ is the industry standard tool for life data analysis. It performs analysis using multiple lifetime distributions, and supports all data types. It is packed with tools for related reliability analysis, such as warranty data analysis, degradation data analysis, reliability test design and so on [7].

Lambda Predict is a standard based reliability prediction software and is very useful where the actual product reliability data is not available [7].

PRODAF (Probabilistic Design and Analysis Framework) is a program that implements a practical, multidisciplinary, design-for-reliability methodology for aerospace systems. This predictive tool plays a key role in evaluating a design's characteristics such as performance and reliability [8].

STRUREL is a collection of software modules for probabilistic modeling in structural engineering. The user-friendly and intuitive GUI assists the user in performing the reliability analysis and in-post processing. COMREL, SYSREL, STATREL and COSTREL are the extensions of STRUREL [9].

DARWIN (Design Assessment of Reliability with INspection) is fracture mechanics and reliability assessment software that supports damage tolerant design and analysis of metallic structural components [10].

NESSUS (Numerical Evaluation of Stochastic Structures Under Stress) is a modular computer software program for performing probabilistic analysis of structural/mechanical components and systems. It treats the parameters of an existing model as random variables to quantify the reliability of design [11].

The probabilistic design software's are intensively being used in different areas of study. The next section will highlight some major areas of application, while focusing mostly on water resources engineering.

Applications

The probabilistic approach has been adopted in different disciplines to ensure higher safety and optimum design. I will be discussing on some examples in water resources where the probabilistic analysis has been widely used.

Probabilistic analysis is used by engineers in designing the storm water detention facilities. The analytical probabilistic method proposed by Becciu, et al (2005) allows estimating the probability distribution function of averages retention times in a storm water detention facility [12].

Probabilistic approach is being used in probabilistic characterization of the productive capacity of a well in a geological formation hosting an aquifer, which can later be used to preliminary assessment of the probability of success for a required productivity (i.e. target point) [13].

Bivariate and multivariate probabilistic analysis are often being used to observe the interaction between different parameters in the system and yields much better results compared to deterministic approaches. Results from such analysis are quiet useful in making decisions where uncertainty is required to be incorporated. A paper by Candela et al. discuss about the probabilistic flood hazard mapping using Copulas which could be very useful in defining spatial development plans for a given flood-prone area or to identify priorities in the organization of civil protection actions [14].

The probabilistic approach is being used in the estimate of design flood for the planning of flood management. Design floods are used to specify the limit up to which a flood should be controlled completely by technical measures, and as they were specified by very small probabilities, the risk of flood beyond the design flood could be considered negligible [15].

The estimation of flood frequency is vital for the flood control strategies and hydraulic structure design. The entropy copula method coupling with the Gibbs sampling technique provides an alternative and better way to statistically model the trivariate flood events [16].

A paper by Tosunoglu represents the first research to model joint distribution functions of annual maximum drought severity and corresponding duration via bivariate copulas. The bivariate return periods of the annual maximum severity and corresponding duration characteristics can provide more useful information for reliable drought risk assessments in the basin [17].

The probabilistic approach is being used in the evaluation of nitrogen, phosphorus and organic removal efficiency during four cycles of Aquifer Storage and Recovery (ASR). The approach was successful in calculating total organic carbon (TOC) and total nitrogen (TN) removal. TOC and TN removal was dominated by redox processes, aerobic respiration and denitrification. However, this approach failed to calculate the removal efficiency of total phosphorous (TP) due to the reversible removal via adsorption and desorption process. Hence, probabilistic approach can be used to characterize the capacity of the anoxic carbonate aquifer treatment barrier [18].

Besides water resources, the probabilistic approach of design has been widely adopted in several other disciplines of study. Probabilistic design is currently being used in seismic hazard analysis. Seismic hazard

is the possibility of having potentially destructive earthquake activities at specific location. Probabilistic seismic hazard analysis is used to determine design earthquakes for site-specific studies such as the siting of critical structures (power plants, waste disposals, large dams, etc.), strategic structures (fire stations, military commands, hospitals, etc.), or for seismic micro zoning studies [19].

In pavement management system (PMS), deterministic approach is applied to estimate the time to maintenance by following the deterioration equation of performance index and the probabilistic approach will further estimate the probability of failure over the estimated time to maintenance. Thus, probabilistic approach in PMS is used to estimate the probability of failure of pavement based on both overall condition and individual distress [20].

Most regulatory agencies and the government endorsed the use of deterministic analysis in decision making. However, studies have shown that the use of deterministic approach can lead to higher risks. In recent years, there has been a drift from deterministic approach to probabilistic approach and such agencies and the government apply probabilistic methods in environmental regulation, where it is called pathway analysis. Probabilistic approach has potential for risk management in developing countries with limited resources, technical expertise and information. The use of probabilistic approach over deterministic analysis helps in saving the expense of design failures and higher risk. Probabilistic analysis may prove to be useful for public policy decisions, such as the regulation of Arsenic in Chile [21].

Another significant application of probability theory in everyday life is reliability. Many consumer products, such as automobiles and consumer electronics, use reliability theory in product design to reduce the probability of failure. Failure probability may influence a manufacturer's decisions on a product's warranty. Probability theory is applied in everyday life in risk assessment and in trade on financial markets. The large insurance corporations are probably the only corporations that devise their entire business strategy around probability and past data. The Department of Defense (America) makes strategies on positioning of its carrier strike groups, its actions and other sophisticated contingency documents which a common civilian or even most of the servicemen are never going to hear about by calculating the probability of coming to execution of any perceived threat to its vessels. Meteorologists also predict the weather based on the patterns of the previous year, temperatures and natural disasters are also predicted on probability and nothing is ever stated as a surety but a possibility and an approximation [22].

Conclusions

So far, the methodology of probabilistic design, different techniques and softwares used and its significance over deterministic approach have been discussed. It is of no doubt that probabilistic approach provides better estimate compared to deterministic approach and provides robust information used in decision making. Nevertheless, it is not completely independent of deterministic approach and is not always a superior technique over deterministic. There are instances where both the approaches must be used as an integrated system to obtain an optimum design, and there are situations where we may wish to go with deterministic approach rather than probabilistic approach. The limitations of deterministic approach have been so far discussed in the introduction section, which were the reasons for increasing supersedence of deterministic approach. This section will aim at highlighting some limitations or the hurdles in probabilistic approach of design.

In real case scenarios, data collection is the most tedious and time-consuming thing. On top of it, data is often limited to accurately estimate the probabilities of the random variables. Basically, when we are concerned at the extreme events, this would be much problematic as we won't be having sufficient data to get a choice of distribution. The probability of failure is calculated from the output distribution. Thus, we need to make a choice of some distribution and often the choice is normal distribution. This will hold true for linear distributions; however, the distribution might not be always normal with problems associated with non-linearity. Thus, there are likely chances that we end up with wrong distribution, and the wrong estimate. Hence, the results from probabilistic approach by default may not be reliable enough for design process.

Mathematical models, both deterministic and probabilistic, can assess only what is modeled, and does not address out of scope phenomena. Results from such models are important inputs to decision making, but they do not constitute a sufficient base of information to address the complex issues that face the nuclear power or aerospace industries. In aerospace industry, the probabilistic approach may help to identify opportunities to enhance airplane or power plant design and operation and to assist in establishing safety significant conditions or events however, it alone cannot ensure the compliance with regulations, replace the design concepts of safety margins and address all considerations associated with risk-significant conditions. The Probabilistic Risk Assessment (PRA), one of the often used comprehensive method of risk analysis does not properly deal with organizational issues, safety culture issues and unexpected events. Therefore, it is important to maintain a constant questioning attitude and to critically consider PRA results [23].

Univariate analysis works well if only one variable is significant in the design process (Salvadori and De Michele 2004), such as design flood at a location, however it will not be viable if the risk results from a coincidence of unfavorable conditions, which cannot be specified by the probability of a flood peak at one reference gauge [15].

Despite the increased acceptance of probabilistic approach, a single value representing risk gives unjustified confidence that the issue has been addressed. The result from this approach should always be followed by further thoughts in decision making process [24].

Also, the predicted failure probability is greatly affected by modelling errors. Techniques to minimize the errors to lowest possible is often adopted however there is always some error which exists in the system as unavoidable errors. And, these errors need to be accommodated in the probabilistic design as additional uncertainties. However, it makes the process complicated and estimating the statistics of modelling errors is extremely difficult as it requires data in large numbers about experimental-analytical mismatch observed in systems of the same kind.

Despite some pronounced limitations discussed above, probabilistic approach is superseding the deterministic approach. With the fundamentals of deterministic approach, the probabilistic design helps in building a robust model and perform reliable analysis such as assessment and risk management of drought and flood risks, analysis of return period and reliability of water structures, an estimate of retention time storm water detention facilities. Besides hydrology, the probabilistic design has been widely introduced in several other disciplines of study including but not limited to engineering designs, geosciences, computer science and medical science. Probabilistic design requires no extra modelling over a deterministic one. The major contributing factor to the lack of probabilistic application is the time to collect data and so-called mathematical sophistication. Thus, if the data required for analysis such as standard deviation, coefficient of variation, mean, etc. are made readily available, and with increased familiarity with probabilistic concepts, the use of probabilistic approach will highly supersede the deterministic approach [1].

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APPENDIX I

Abstract

Summary of the project is addressed on this section.
Word count: 196 (required~200)
Page 2

Introduction

It covers the introduction of deterministic and probabilistic approach and highlights the difference between these two approaches.
Word count: 800 (required~800)
Page 2,3

Probabilistic Design Methodology

This section covers the various approaches and software used in probabilistic design.
Word count: 928 (required~900)
Page 4,5,6

Applications

It covers the distinct applications of probabilistic design methods.
Word count: 884 (required~900)
Page 7,8

Conclusions

It covers the last 2 sections of report: limitations and conclusion.
Word count: 764 (required~750(600+150))
Page 9,10

References

Page 11,12

Total word count: 3572* (~3550)

Note: All the word counts are inclusive of titles and headings.

APPENDIX II

"Probabilistic approach in Water Resources Engineering: Increasing supersedence of Deterministic approach while acknowledging the fundamentals of Deterministic design."

Hydrology is often accompanied with lots of uncertainties and extremities and there has been an increasing challenge for people in water resources to capture the physical process. The concept of stationarity and deterministic approach was the fundamentals used in understanding the hydrological phenomena. However, there is no guarantee that the process follows stationarity and the deterministic and statistical approach will give us the desired results. Nevertheless, they are always the fundamentals and should be acknowledged. But, with the complexity of the system and the associated uncertainty, there has been a need for a probabilistic approach to better understand and analyze the results. The probabilistic design is a novel approach which no longer deals with specific values or numbers but assumes every event as a random variable and looks for the occurrence of such events.

In recent years, it has been observed that the probabilistic approach is superseding the deterministic approach. With the fundamentals of deterministic approach, the probabilistic design helps in building a robust model and perform reliable analysis such as assessment and risk management of drought and flood risks, analysis of return period and reliability of water structures, an estimate of retention time storm water detention facilities. Besides hydrology, the probabilistic design has been widely introduced in several other disciplines of study including but not limited to engineering designs, geosciences, computer science and medical science.