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Reliability Analysis of Possible Modes of Failures in the Counterfort Retaining Wall

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Abstract: Engineering decisions must be made in the presence of uncertainties which are invariably present in practice. In the presence of uncertainties in the various parameters encountered in analysis and design, achievement of absolute safety is impossible. In structural reliability, the probability of failure (which is taken as one minus reliability) is taken as quantitative measure of structural safety. Probabilistic concepts are used in reliability analysis, and in the design of structures. Using structural reliability theory, the level of reliability of the existing structures (structures designed by existing structural standards) can be evaluated. In this work, various probabilistic concepts for Reliability based design are studied. A limited study of System Reliability of RC Counterfort Retaining wall, based on certain assumptions is made in this project. A MATLAB program has been written for analysis and design RC Counterfort Retaining Wall as per IS 456-2000. One more program has also been written for computing the reliability of the designed retaining wall. For the considered system, the safety margin equations have been developed for various failure modes. Angle of internal friction of backfill material, SBC of the foundation soil, characteristic strength of steel and concrete are considered as random variables in our project.
Keywords: Structural Reliability, Probability, Counter fort, Safety Margin, Random Variables

I. INTRODUCTION

The reliability of a structure is its ability to fulfil its design purpose for some specified design life time. Reliability is often understood to equal the probability that a structure will not fail to its intended function. The term "Failure" does not necessarily mean catastrophic failure it is used to indicate that the structure does not perform as desired. Many sources of uncertainty are inherent in structural design. Despite what we often think, the parameters of the loading and the load-carrying capacities of structural members are not deterministic quantities (i.e. quantities which are perfectly known) cannot be achieved. Consequently, structures must be designed to serve their function with a finite probability of failure. Society expects Buildings, Bridges and Retaining walls are to be designed with a reasonable safety level. In practice, the expectations are achieved by following code requirements specifying design values for minimum strength, maximum allowable deflection, and so on. Code requirements have evolved to include design criteria that take into account of the sources of uncertainty in design. Such criteria are often referred to as reliability-based design criteria.

A. Uncertainties In Engineering Design

In engineering design, there are a number of uncertainties that result from the variability of applied loads and material properties, in addition to that resulting from the design modeling. Also, during manufacturing, a number of uncertainties arise from the manufacturing processes and from the material selection. The problem of uncertainty in estimating the loads can be clearly noticed in the aerodynamic and hydrodynamic loads that are considered in the design of aircrafts and ships. As these loads are not known exactly, aerospace and naval designers have to consider some kind of statistical representation of these loads. Also, it is known that the material properties documented in the material specification handbooks and manuals are not the exact properties of the actual product. Since these documented material properties are taken from the averages of the measured experimental data. Also, the experiments were performed in laboratory conditions that may differ from the situation in hand. In addition, some material defects, such as micro-cracks and voids, can seriously weaken the material and may be very difficult to detect. Likewise, in some applications, the material may experience environmental deterioration (such as corrosion and abrasion), that may not be quantified with certainty. Moreover, there are uncertainties in manufacturing the components of engineering systems despite the quality control measures that are applied. The reason is that inspection for quality is performed most of the time on some random samples of the components and not on all the components; otherwise, the cost will be prohibitively high. Finally, in modeling the engineering systems a number of idealizations may be made to simplify the analysis, which will result in reducing the accuracy in representing the real system. However, these idealized engineering system designs are rarely produced with the exact dimensions specifications, since tolerances must be given for material processing and fabrication, which adds to the level of uncertainty in the design.

B. Designing With Uncertainty

1) *Deterministic Design:* A designer must deal with the existence of uncertainties in the product in a manner that will make the design perform as expected in a safe and reliable way. For that purpose, two methods have been developed over the years to quantify the uncertainties in an engineering product and their effects on the design level of safety. The first approach is the deterministic design, in which it is assumed that all the information about the design is known and a conservative assumption is made to compensate for any unaccounted factors. Accordingly, a factor of safety or a load factor is assigned to either the material strength or the applied loads and it is the representation to the design level of safety. The second approach is the reliability-based design, in which it is assumed that the information about the design is known to be within certain bounds and have known distributions of probability. Accordingly, the probability of survival of the design is calculated and can be considered to represent the level of safety of the design. The deterministic approach considers average values for the loads and material properties. It does not consider quantitatively the frequency of occurrence of some particular values of the loads and material properties during the life-span of the product. Instead, a subjective value is assigned to the factor of safety or the load factor on a qualitative basis. Also, the deterministic approach becomes highly subjective in the sense that factor of safety is usually estimated and modified according to the cost and the consequences of failure of a particular component. In addition, the deterministic approach does not use a quantitative method for combining variable loads that are applied to the design. Thus, the level of safety of an engineering design that has multiple components that differ in their required level of safety will not be consistent, because the overall level of safety of a system can not be determined from adding the safety factors of the individual components. As a result, an overestimation or underestimation of the design level of safety will be made. Finally, it must be noted that the deterministic approach does not identify the parts or regions of the design that may fail much earlier than others, and also, does not identify the more critical loads or design variables since all the uncertainties are covered by one factor throughout the design.
2) *Probabilistic Design:* On the other hand, the reliability of an engineering design is calculated using statistical analysis and probability principles to the samples of the expected service loads and the properties of the material used in the design. The uncertainties are modeled by randomly distributed variables, in which the frequency of occurrence of each possible value of the variable is considered. Specifically, the most repeated values of a random variable are associated with the highest values in the probability distribution function. However, it must be noted that there are some experience-based assumptions that are made in determining the type and shape of the probability distribution of each random variable, since it is impossible to perform experiments that cover all the possible values of a random variable. Nevertheless, the accuracy of the model used to represent the actual data increases as the volume of the available statistical data increases. For example, flight loads spectra can now be generated with considerable accuracy. Also, by tightening the quality measures and by using more accurate models, a better assessment of the design safety may be achieved. Once the uncertainties are modeled, a consistent level of safety can be obtained for the engineering design. In particular, the failure of an engineering system that has multiple components with different safety levels may be defined by combining the reliabilities of the components as in the following. In the case of independent failures, the reliabilities can be combined in serial (failure of one component makes the whole system fail) and/or in parallel (failure of all components makes the whole system fail.) Also, in the case of correlated failures, joint probabilities of failure can be calculated for the design. Hence, the uncertainties present in the design can be quantified and calculations of the safety level can be performed in a more coherent manner.

II. LITRATURE REVIEW

Luis. M.C.Simoes and Joao. H.O.Negrao (2005) presented a procedure for finding the reliability based optimum design of cable stayed bridges. The minimization problem is stated as minimization of stresses, displacement, reliability and bridge cost. A finite element approach is used for structural analysis. Jiansens Zhang, Ricardo O. Foschi (2004) applied reliability analysis to estimate probability of failure in each set of performance requirements. Probability estimation was conducted through Monte Carlo Simulations with variations reduction techniques. Neural networks were directly employed or the reliability assessment and design. Manollis Prapadrakakis, Yannis Thosmpanakis (2004) proposed a methodology that combines structural optimization and structural reliability procedure for the design of steel moment resisting frames. Additional probabilistic constraints were imposed in order to control the uncertainties on load bearing and deformation capacity of the structure. M. Papadrakakis, etal (2002) associated the failure of the structural system with the plastic collapse. Reliability analysis carried out with the Monte Carlo Simulation (MCS) method incorporating the importance sampling technique for the reduction of the sample size. Jung won Huh, Achintya Haldar (2002) proposed a reliability analysis algorithm for Non-linear structures, where seismic loading canbe applied in the time domain.

The method is developed specifically for steel frame structures considering all major sources of Non-linearity, including geometry, material and partially restrained connections. Bong Koo Han, Hyo Nam Cho and Sung Pil Ghang (2001) presented a reliability based design and code calibration for concrete containment structure. In this study, a Load combination criterion for design and probability-based reliability analysis were proposed. The limit state model defined for the study of the crack failure that cause the emission of radioactive materials and the results are compared with the case of strength limit state. Y.K. Wen (2001) proposed a reliability based frame work for design for proper consideration and treatment of large uncertainty in the loading and the complex buildings behavior in the Non-linear range in the evaluation and design process. Minimum lifecycle cost criteria were proposed to arrive at optimal target reliability for performance based design under multiple natural hazards. S.W. Han, Y.K. Wen (1997) conducted study on the method of reliability based seismic design. In reliability analysis and reliability analysis and reliability based design under stochastic loads such as seismic excitations, repeated time-history solutions of multiple degree of freedom inelastic structures are often required, which can become computationally expensive. To alleviate this difficulty, authors developed an approximate method by replacing the MDOF system with a simple equivalent non linear system. C.C. Chang, J.F. Ger and F.Y. Cheng (1992) conducted study on steel structure subjected to seismic loading of the uniform building code and new-marks distribution of response and resistance with two variance approaches. Two objective functions of weight and cost, and carious constraints such as displacement, yielding, buckling of constraint members are considered. They studied sensitivities of parameters such as variation approaches and interacting ground motion on optimum solutions.

III.PROBABILITY THEORY

Probability theory had its origin in the analysis of certain games of chance that were popular in the seventeenth century. It has since found application makes it an important branch of study. Probability theory, as a matter of fact, is a study of random or unpredictable experiments and is helpful in investigating the important features of these random experiments. An experiment whose outcome or result can be predicted with certainty is called a deterministic experiment. Although all possible outcomes of an experiment may be known in advance, the outcome of particular performance of the experiment cannot be predicted owing to a number of unknown causes. Such an experiment is called a random experiment. Let S be the sample space (the set of all possible outcomes which are assumed equally likely) and A be an even (a subset of S consisting of possible outcomes) associated with a random experiment. Let n(S) and n (A) be the number of elements of S and A. then the probability as P (A) is defined by

$$P(A) = \frac{n(A)}{n(S)}$$

n(A) = Number of cases favorable to A

n(S) = Exhaustive number of cases in S

Let a random experiment be repeated n times and let an event A occur nA times out of the n trials. The ratio nA/n is called the relative frequency of the event A. as n increases; nA/n shows a tendency to establish and to approach a constant value. This value, denoted by P (A), is called the probability of the event A, i.e,

$$P(A) = \lim_{n\to\infty} \frac{n(A)}{n}$$

Classical Probability: $P(E) = \frac{N(E)}{N(S)}$

Relative Frequency: $P(E) = \frac{N(E)}{N}$ with $N \to \infty$

Subjective Probability

Three Basic Axioms are

$$0 \le P(E) \le 1$$

$$P(S) = 1$$

$$P(E1 \cup E2) = P(E1) + P(E2) \text{ if } E1 \cap E2 = \varphi$$

A. Probability Function

If X is discrete Random Variable which can take the values X1, X2, X3 such that $P(X = xi) = pi$, then pi is called the probability function provided pi satisfy the following conditions.

(a) $pi \ge 0$, for all i

(b) $\Sigma\ pi = 1$

1) Probability Density Function: If X is a continuous Random Variable such that

$P\left(x-\frac{1}{2}dx \le x \le x+\frac{1}{2}dx\right) = f(x)\,dx$

Then f(x) is pdf of x, provided f(x) satisfies the following conditions.

a) $f(x) \ge 0$, for all $x \in Rx$, and

b) $\int f(x)\,dx = 1$

2) Cumulative Distribution Function: If x is an Random Variable discrete or continuous then,

$P(X \le x)$ is called the cumulative distribution function.

If X is discrete,

$F(x) = \Sigma P_j, X_j \le x$

If X is continuous,

$F(x) = P(-\infty < X \le x) = \int f(x)\,dx, -\infty < X \le x$

B. Normal Probability Distribution

A continuous random variable X is said to follow normal distribution, with mean μ and standard deviation σ, if its probability density function is given by

$$y = f(x) = \frac{1}{\sigma\sqrt{2\Pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

The mean μ and the standard deviation σ are called the parameters of the normal distribution.

Remark: A random variable X with mean μ and variance σ^2 and following the above said equation is expressed by $X \sim N(\mu,\sigma^2)$.

1) Properties and Constants of Normal Distribution:

Mean = μ

Variance = σ^2

Standard deviation = σ

a) The normal curve is bell shaped and symmetrical about the line

$X = \mu$.

b) Mean, median and mode of the distribution coincide,

Thus $mean = median = mode = \mu$.

c) As X increases numerically, f(x) decreases rapidly. The maximum probability occurs at the point $x = \mu$, and is given by

d) P(x) max = $\frac{1}{\sigma\sqrt{2\Pi}}$

e) X axis is an asymptote to the curve.

f) It has only one mode at $x = \mu$.

g) Since the curve is symmetrical, skewness is zero.

h) The points of inflection of the normal curve are $x = \mu \pm \sigma$

i) Area property:

$P(\mu - \sigma < x < \mu + \sigma) = 0.6826$

$P(\mu - 2\sigma < x < \mu + 2\sigma) = 0.9544$

$P(\mu - 3\sigma < x < \mu + 3\sigma) = 0.9973$

C. Reliability

Since the goal is to determine the level of safety of a design in its service environment, it would be very expensive to apply actual loads to the design and calculate the chance of failure. Instead, computer based analytical models are used to simulate the behaviour of the design under different conditions, and then, the results are used to calculate the reliability of the design. The number of simulation runs is related to the number of uncertainties present in the design parameters or loads. Accordingly, the design is evaluated every time with a different set of values of the random variables. In turn, the values of the random variables that enter every valuation run are selected according to their respective probability distribution. After that, statistical methods are used to evaluation the output and predict the reliability of the design. For example, if we consider a simple design such as a rod that has a strength R that may vary from one rod to the other (depending on some unknown manufacturing conditions). However, it was known that from previous samples, a statistical distribution of the rod's strength was obtained. Then the strength of the rod can be

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represented by a randomly distributed variable with a known probability density function (PDF). Now, if we have a stress S that acts on the rod that has a magnitude that varies randomly, we know that the event of failure occurs when:

$R - S < 0$ -------------------------- 4.1

Now, to calculate the reliability of the rod we need to calculate the probability of occurrence of the failure event, which can occur at any point inside the failure domain Ω that is represented graphically by the shaded area in Figure.

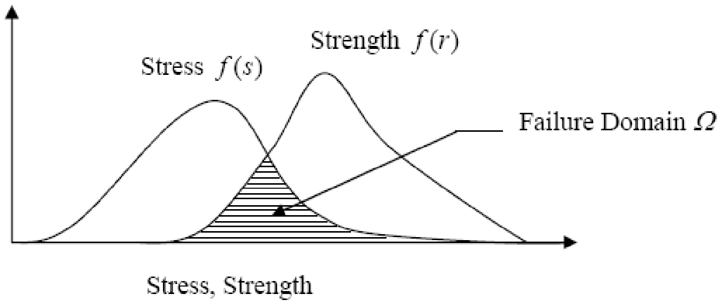

Fig15. Overlap of Stress and Strength Distributions Indicating Failure Probability

So, in the case that the rod's strength and the applied stress values are statistically independent, the probability of failure Pf for this simple example can be calculated from the following integral:

$P_f = \iint_{\Omega} f(r) f(s) \, dr \, ds$ ------------------------------ 4.2

However, despite that the integral of equation can have a direct analytical solution for some special cases, or can be performed numerically for some other cases, in most real life situations the integral cannot be evaluated directly. In many cases the failure domain Ω may not have an analytical expression and the problem gets more complicated as the number of random variables increases. Thus, other methods such as the simulation-based reliability methods (Monte-Carlo Simulation methods), or the analytical reliability approximation methods (e.g. the first and second order reliability methods, and the advanced mean value method) must be employed.

1) *Analytical Reliability Approximation Methods:* To calculate the reliability of a design we may need to use a suitable way to approximate the integral in equation (4.2). However, depending on the types of the functions involved and the shape of the failure region Ω, we may be able to approximate the reliability by using first or second order Taylor series approximation to the limit state function (or the performance function) G(X). In the following sub-sections we are going to present one of the widely used methods and refer to other existing methods.

2) *The First Order Reliability Methods (FORM) :* This method is a development of the fast probability integration method FIP and the name first order reliability method comes from approximating the performance function G(X) by a first order Taylor series. Also, when we are only considering the first two moments of the random variables (for normally distributed random variables, the first moment is mean value, and the second is the variance), and ignoring the higher moments (i.e. skewness, flatness etc.), then these methods are called the first-order second-moment methods (FOSM). However, before we present some of the FORM methods, it is appropriate to define the Cornell safety (or reliability) index (β).

3) *The Cornell Reliability Index:* The Cornell reliability index was the first analytical approximation method to calculate the probability of failure, and it had paved the way for other methods that have a wider domain of application. To introduce it in a simple way, let's recall the simple example of the rod under load presented in Sec. 2.1, where we had the following simple limit state function

$G(\bar{x}) = R - S$ --- 4.3

Assuming that R and S are statistically independent and normally distributed random variables, we may define a new random variable Z with the following properties.

$Z = R - S$

$\mu_z = \mu_R - \mu_S$

$\sigma_Z^2 = \sigma_R^2 - \sigma_S^2$ -- 4.4

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Where μ_Z and σ_Z are the mean value and the standard deviation of the random variable Z respectively. Then the probability of failure can be calculated from

$$P_f = P[Z < 0] = \varphi\left(-\frac{\mu_Z}{\mu_Z}\right) = \varphi(-\beta) \text{ ------------- 4.5}$$

Where $\varphi(\beta)$ is the cumulative distribution function for a standard normal variable, and β is the safety index. The same concept can be generalized to the case of more than two random variables and to the case of nonlinear performance function and this can be done by Taylor series expansion of the performance function around the mean values of the random variables as in the following:

$$Z = g(\bar{X}) + \sum_{i=1}^{n} \frac{\partial g}{\partial x_i}(x_i - \bar{x}_i) + \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n} \frac{\partial^2 g}{\partial x_i \partial x_j}(x_i - \bar{x}_i)\left(x_j - \bar{x}_j\right) + \cdots$$

--------------- 4.6

Where g(X) is the performance function evaluated at the mean values of the random variables, and xi is the mean value of the random variable xi. Then, if we truncate the series at the linear terms, the first approximate mean value and the variance of Z will be given by

$$\mu_Z \approx g(\bar{X})$$

$$\sigma_Z \approx \left(\sum_{i=1}^{n}\sum_{j=1}^{n} \frac{\partial g}{\partial x_i}\frac{\partial g}{\partial x_j} \mathrm{Conv}\left(x_i, x_j\right)\right)^{\frac{1}{2}} \text{ ---------------- 4.7}$$

Where conv (x_i, x_j) is the coefficient of variation for the random variables x_i, x_j.
Also, a better estimation of the mean value of Z can be obtained from considering the square term in the Taylor series

$$\mu_Z \approx g(\bar{X}) + \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n} \frac{\partial^2 g}{\partial x_i \partial x_j} \mathrm{Conv}\left(x_i, x_j\right) \text{ --------- 4.8}$$

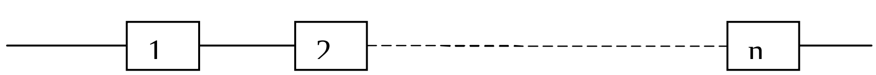
However, the second order variance requires obtaining the higher moments of the random variables, which may not be available in practical situations. Finally, the safety index β, and the probability of failure can be determined from (Eq. 4.5) as before. Also, since the limit state function is linearized around the mean value, the safety index method is also known as the mean value first-order second-moment (MVFOSM). However, it is important to know that the estimation of the probability of failure using the safety index can only give accurate values for special cases, particularly, when the performance function is a simple addition or multiplication of the statistically independent random variables. Also, it gives different reliability values for the same design problem if the formulation of the performance function is changed to an equivalent formulation (i.e. this reliability calculation method lacks invariance). Thus, there was a need to develop some improved methods that avoid this problem (some of them will be presented shortly). Yet, these improved methods are based on the safety index idea, which from equation 4.5 we can see that it gives a qualitative measure of safety, in the sense that larger values of β means safer design, and vice versa.

D. Reliability Of Counter fort Retaining Wall

A structural system may have several failure modes. These failure modes are to be identified, modelled, and combined to determine the system reliability. Hence the reliability of structures/ structural system of multiple components and with multiple failure modes is to be considered from the system point of view. One of the important applications of probability theory is the evaluation of the reliability of a system which is made up of components with known reliabilities. The reliability of a component is the probability of its satisfactory performance against the purpose for which it has been designed. Block diagrams are used to demonstrate the computation of the reliability of a system. Systems are classified basically into three groups,

1) Series System: The term, commonly used in the field of electrical engineering, is easily understood by everyone. In this system, even if one component fails to function satisfactorily the whole system will fail. Therefore, a series system performs satisfactorily only when every component works satisfactorily. The reliability of the system is calculated as explained below,

Let A1 = the event that component i works satisfactorily
Pss = probability of survival of the system
Pfs = Probability of failure of the system
Pss = 1-Pfs



Series System

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As every component should function satisfactorily for the system to be reliable,

$$P_{ss} = P\,(A1 \cap A2 \cap \ldots \cap An)$$

If the events Ai are independent, the above equation simplifies to

$$P_{ss} = P\,(A1)\,P\,(A2)\ldots P\,(An)$$

$$P_{ss} = \prod_{i=1}^{n} (1 - P_{fi})$$

Where,

P_{fi} = the probability of failure of the component i, and

n = the number of components.

The model is also called the “weakest link model”.

In the case of structural system in civil engineering, the values of Pfi are very small. If Pfi <<1,

$$P_{ss} \approx 1 - \sum_{i=1}^{n} P_{fi}$$

2) *Parallel System:* In this case, the system survives even if one component has failed. The system fails to function satisfactorily only when every component of the system has failed to function satisfactorily. The block model diagram for the computation of reliability is shown below.

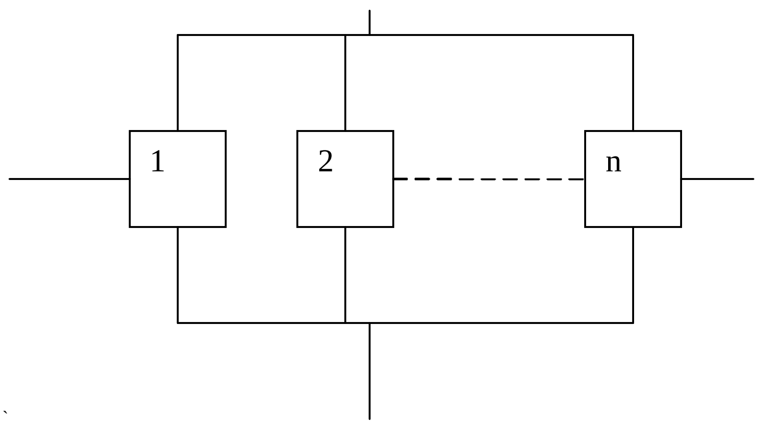
$$P_{ss} = 1 - P_{fs}$$

$$= 1 - P\,(A1 \cap A2 \cap \ldots \cap An)$$

Where A1= the event that component i, does not function satisfactorily. If event A1 are independent,

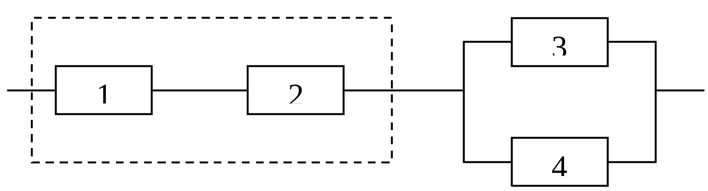
$$P_{ss} = 1 - [P\,(A1)\,P\,(A2) \ldots P\,(An)]$$

$$= 1 - \sum_{i=1}^{n} P_{fi}$$



Parallel system in structural engineering, this system may be referred to as parallel system with n perfectly ductile elements.

3) *Mixed System:* This is a combination of series and parallel redundant systems. The block model diagram for the computation of the reliability of a mixed system is shown below. This is visualized to consist of subsystem S1 and S2.



MIXED SYSTEM

Where E1= the event that subsystem 1 functions satisfactorily and E2= the event that subsystem 2 functions satisfactorily. Knowing how to compute the system reliability of the series and parallel redundant systems, the probability of the survival of this mixed system,

$$P_{ss} = P\,(E1)\,P\,(E2)$$

$$= (1 - P_{fs1})\,(1 - P_{fs2})$$

Where Pfs is the probability of failure of the subsystem i. It has been assumed that events A1 are statistically independent.

E. Approximations Of Performance Functions

In structural analysis, sometimes the performance function G(X) can be obtained as a closed-form equation, which will allow direct application of standard optimization techniques (see next subsection for a short review of some of the commonly used optimization methods for reliability calculation and reliability-based optimization) needed to calculate the design reliability using FORM. Also, in some other situations the performance function of the design may not be explicit, but may have just one random variable and may be approximated linearly or quadratic ally during optimization. Yet, it was realized that in many other structural designs the performance function can not be represented by closed-form equations nor has more than one random variable. This situation occurs mostly when failure is simulated point by point in finite element analysis. In those applications, a high non-linearity and possible discontinuities may occur especially In the case of sudden failure (e.g. buckling or crack propagation) and in the case of multiple failure modes. However, it may become computationally expensive to make a point-by-point discovery of the entire failure domain. Also, to ensure convergence of the optimization process that the FORM methods use to calculate reliability, a differentiable (or if possible) a closed-form of the performance function should be obtained. Therefore, it would be beneficial to approximate the performance function rather than having it in point-by-point format. For this purpose, researchers have used different methods to approximate the structural response. For instance, some researchers have developed analytical gradients of the performance function with respect to the random variables by reformulating the finite element model. This was done to facilitate the optimization process needed to perform FORM and SORM, since there were some difficulties in numerical calculation of these gradients. Yet, in general, it may not be easy to reformulate all other finite element models especially those that are a part of a general purpose code. However, sensitivity derivatives can be obtained from the stiffness matrix of the finite element model, and thus, may have wide range of applications was developed. Despite that, it would be preferable to find a way to approximate the performance function for the case of multiple failure modes, which normally results in derivative discontinuity in the performance function approximation. Therefore, other methods have been employed. These methods range from linear and quadratic response surface (RS) methods, which were employed by many researchers, to higher order approximations that take into account possible derivative discontinuity. However, it should be noted that the use of RS and similar methods gets to be computationally very expensive as the number of random variables increases.

IV. RELIABILITY ANALYSIS OF COUNTERFORT RETAINING WALL

Now the interest is to determine the reliability index for the above designed Counterfort Retaining wall which is designed based on the deterministic approach as prescribed by IS 456 - 2000. In order to determine the reliability index, the necessary safety margins are needed to be developed for the expected failure modes. In this unit, the safety margins have been developed and the corresponding MATLAB code required determining the reliability index. In this retaining wall design, the following parameters are taken as random variables. While rest of the parameters are assumed to be constant within the design.

Yield strength of steel, fy
Compressive strength of concrete, fck
Angle of internal friction, φ
Coefficient of friction, μ
Safe Bearing Capacity of soil, SBC

A. Inputs Required For The Developed Code

The following inputs are required for the program developed by us to determine the reliability index of the Counterfort Retaining wall.

1) Density of soil (γ)
2) Co-efficient of friction (μ)
3) Angle of internal friction (φ)
4) Safe Bearing Capacity of soil
5) Yield strength of steel (fy)
6) Compressive strength of concrete (fck)
7) Mean value coefficient of friction
8) Standard deviation of coefficient of friction
9) Mean value of angle of repose
10) Standard deviation of angle of repose

11) Mean value of Safe bearing capacity
12) Standard deviation value of Safe bearing capacity
13) Mean value of strength of concrete
14) Standard deviation of strength of concrete
15) Mean strength of steel
16) Standard deviation of strength of steel

B. Developments Of Safety Margin Equations

1) *Reliability in failure mode 1: Sliding:* The retaining wall has the tendency to slide under the action of horizontal component of active earth pressure which is resisted by the frictional force at the base of retaining wall and the passive earth pressure. Generally the passive is small if the height of earth in front of retaining wall is small and neglected.

If, safe $\mathrm{P} < \mu\mathrm{W}$

Safety margin, $\mathrm{Z} = \mu\mathrm{W} - \mathrm{P}$

$$\mu\mathrm{W} = \text{Resistance}$$

$$\mu_{\mu W} = W\mu_{\mu}$$

$$\sigma_{\mu W} = W\sigma_{\mu}$$

$$\mu_P = \frac{k_a\gamma H^2}{2}$$

$$\sigma_P{}^2 = \left[\left\{\frac{\partial P}{\partial \varphi}\right\}_{\mu}\right]^2 \sigma_{\varphi}{}^2$$

$$\left\{\frac{\partial P}{\partial \varphi}\right\}_{\mu} = \frac{\gamma H^2}{2}\left(\frac{-2\cos\varphi}{(1+\sin\varphi)^2}\right)$$

$$\mu_Z = \mu_{\mu W} - \mu_P$$

$$\sigma_Z = \sqrt{\sigma_{\mu W}{}^2 + \sigma_P{}^2}$$

From μ_Z and σ_Z we can calculate the Probability of Failure.

2) *Reliability in failure mode2*: Bearing Capacity: Any foundation should be designed to safely transmit the load to the underlying soil so that its bearing capacity is not exceeded. If the maximum pressure on the retaining wall exceeds the safe bearing capacity of the soil the failure will occur. Also, we know SBC of the soil is a highly variable parameter. It has been accommodated as a normally distributed parameter in our program while calculating the reliability index for a retaining wall in this mode of failure.

If safe $P_{max} < SBC$

Safety margin, $Z = SBC - P_{max}$

$$\mu_{SBC} = 3 \times SBC$$

$$\mu_{P_{max}} = \frac{W}{B}\left(1 + \frac{6e}{B}\right)$$

$$e = \frac{\sum M}{\sum W} - \frac{B}{2}$$

$$\mu_{P_{max}} = \frac{W}{B}\left\{1 + \frac{6}{B}\left(\frac{\sum M}{\sum W} - \frac{B}{2}\right)\right\} = \frac{W}{B}\left\{1 + \left(\frac{6}{B}\frac{\sum M}{\sum W} - 3\right)\right\}$$

$$\mu_{P_{max}} = \frac{W}{B}\left(\frac{6}{B}\frac{\sum M}{\sum W} - 2\right) = \frac{6\sum M}{B^2} - \frac{2W}{B}$$

$$\mu_{P_{max}} = \frac{6}{B^2}\left[w_1a_1 + w_2a_2 + w_3a_3 + \frac{k_a\gamma H^3}{6}\right] - \frac{2W}{B}$$

$$\mu_{P_{max}} = \frac{6}{B^2}\left[w_1a_1 + w_2a_2 + w_3a_3\right] - \frac{2W}{B} + \frac{\gamma H^3}{B^2}\left\{\frac{1-\sin\varphi}{1+\sin\varphi}\right\}$$

$$\sigma_{P_{max}}{}^2 = \left[\left\{\frac{\partial P_{max}}{\partial \varphi}\right\}_{\mu}\right]^2 \sigma_{\varphi}{}^2$$

$$\left\{\frac{\partial P_{max}}{\partial \varphi}\right\}_{\mu} = \frac{\gamma H^3}{B^2}\left(\frac{-2\cos\varphi}{(1+\sin\varphi)^2}\right)$$

$$\mu_Z = \mu_{SBC} - \mu_{P_{max}}$$

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$$\sigma_Z = \sqrt{\mu_{SBC}{}^2 + \sigma_{P_{max}}{}^2}$$

From μ_Z and σ_Z we can calculate the Probability of Failure.

3) *Reliability in failure mode 3:* No Tension at Base: It is a well known fact that soil will not take tension. All our major designs are to make sure that the eccentricity of the load should be avoided in order to avoid tension at base. This mode calculates the reliability of the structure in the No Tension at base.

If safe $\quad e < \frac{B}{6}$

Safety margin, $\quad Z = \frac{B}{6} - e$

$$e = \frac{\sum M}{\sum W} - \frac{B}{2}$$

$$\mu_Z = \frac{B}{6} - \left(\frac{\sum M}{\sum W} - \frac{B}{2}\right) = \frac{2B}{3} - \frac{\sum M}{\sum W}$$

$$\mu_Z = \left[\frac{B}{3} - \frac{W_1a_1 + W_2a_2 + W_3a_3}{\sum W} - \frac{k_a\gamma H^3}{6\sum W}\right]$$

$$\left\{\frac{\partial Z}{\partial \varphi}\right\}_{\mu} = \frac{\gamma H^3}{6\sum W}\left(\frac{-2\cos\varphi}{(1+\sin\varphi)^2}\right)$$

$$\sigma_Z = \sqrt{\left[\left\{\frac{\partial Z}{\partial \varphi}\right\}_{\mu}\right]^2 \sigma_\varphi{}^2}$$

From μ_Z and σ_Z we can calculate the Probability of Failure.

4) *Reliability in failure mode -4 Formation Plastic Yield Line at Stem Wall*: If a deformable structure in equilibrium under the action of a system of external forces is subjected to a virtual deformation compatible with its condition of support, the work done by these forces on the displacements associated with the virtual deformation is equal to the work done by the internal stresses on the strains associated with this deformation. The work done during small motion of collapse mechanism is equal to work absorbed by the plastic hinges formed along the yield lines. The segments of the slab within the yield lines go through rigid body displacements with the collapse load acting on the structure. The following Three failure modes (4,5&6) will obey the above Plastic Yield Line Theory.

If safe $\quad M_a < M_R$

Safety margin, $\quad Z = M_R - M_a$

$$\mu_{M_R} = f_y A_{sts} d \left[1 - \frac{0.77 f_y A_{sts}}{b d f_{ck}}\right]$$

$$\sigma_{M_R}{}^2 = \left[\left\{\frac{\partial M_R}{\partial f_y}\right\}_{\mu}\right]^2 \sigma_{f_y}{}^2 + \left[\left\{\frac{\partial M_R}{\partial f_{ck}}\right\}_{\mu}\right]^2 \sigma_{f_{ck}}{}^2$$

$$\left\{\frac{\partial M_R}{\partial f_y}\right\}_{\mu} = A_{sts} d \left[1 - \frac{1.54 f_y A_{sts}}{b d f_{ck}}\right]$$

$$\left\{\frac{\partial M_R}{\partial f_{ck}}\right\}_{\mu} = \frac{0.77 f_y{}^2 A_{sts}{}^2}{b f_{ck}{}^2}$$

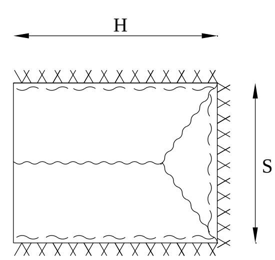
$$\mu_{M_a} = \frac{k_a \gamma H S^2}{48} \tan\alpha^2$$

$$\sigma_{M_a}{}^2 = \left[\left\{\frac{\partial M_a}{\partial \varphi}\right\}_{\mu}\right]^2 \sigma_\varphi{}^2$$

$$\frac{\partial M_a}{\partial \varphi} = \frac{\gamma H S^2}{48} \tan\alpha^2 \left(\frac{-2\cos\varphi}{(1+\sin\varphi)^2}\right)$$

$$\mu_Z = \mu_{M_R} - \mu_{M_a}$$

$$\sigma_Z = \sqrt{\sigma_{M_R}{}^2 + \sigma_{M_a}{}^2}$$



From μ_Z and σ_Z we can calculate the Probability of Failure.

5) *Reliability in Failure mode- 5 Formation Plastic Yield Line at Heel Slab Middle:*

If safe $\quad M_a < M_R$

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Safety margin, $Z = M_R - M_a$

$$\mu_{M_R} = f_y A_{sth} d \left[1 - \frac{0.77 f_y A_{sth}}{bdf_{ck}}\right]$$

$$\sigma_{M_R}{}^2 = \left[\left\{\frac{\partial M_R}{\partial f_y}\right\}_\mu\right]^2 \sigma_{f_y}{}^2 + \left[\left\{\frac{\partial M_R}{\partial f_{ck}}\right\}_\mu\right]^2 \sigma_{f_{ck}}{}^2$$

$$\left\{\frac{\partial M_R}{\partial f_y}\right\}_\mu = A_{sth}\, d \left[1 - \frac{1.54 f_y A_{sth}}{bdf_{ck}}\right]$$

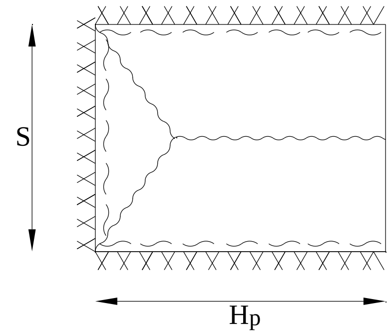
$$\left\{\frac{\partial M_R}{\partial f_{ck}}\right\}_\mu = \frac{0.77 f_y{}^2 A_{sth}{}^2}{b f_{ck}{}^2}$$

$$\mu_{M_a} = \frac{H_{up}\gamma H S^2}{48} \tan \alpha^2$$

$$\sigma_{M_a}{}^2 = \left[\left\{\frac{\partial M_a}{\partial \varphi}\right\}_\mu\right]^2 \sigma_\varphi{}^2$$

$$\mu_Z = \mu_{M_R} - \mu_{M_a}$$

$$\sigma_Z = \sqrt{\sigma_{M_R}{}^2 + \sigma_{M_a}{}^2}$$



From μ_Z and σ_Z we can calculate the Probability of Failure.

6) *Reliability in Failure mode-6 Formation Plastic Yield Line at Heel Slab End*:

If safe $M_a < M_R$

Safety margin, $Z = M_R - M_a$

$$\mu_{M_R} = f_y A_{sth} d \left[1 - \frac{0.77 f_y A_{sth}}{bdf_{ck}}\right]$$

$$\sigma_{M_R}{}^2 = \left[\left\{\frac{\partial M_R}{\partial f_y}\right\}_\mu\right]^2 \sigma_{f_y}{}^2 + \left[\left\{\frac{\partial M_R}{\partial f_{ck}}\right\}_\mu\right]^2 \sigma_{f_{ck}}{}^2$$

$$\left\{\frac{\partial M_R}{\partial f_y}\right\}_\mu = A_{sth}\, d \left[1 - \frac{1.54 f_y A_{sth}}{bdf_{ck}}\right]$$

$$\left\{\frac{\partial M_R}{\partial f_{ck}}\right\}_\mu = \frac{0.77 f_y{}^2 A_{sth}{}^2}{b f_{ck}{}^2}$$

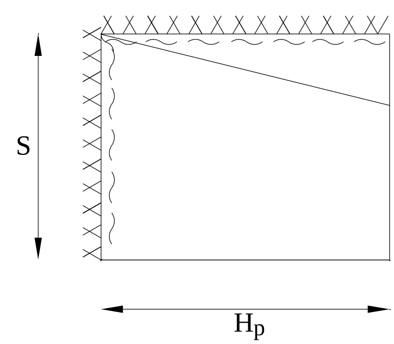
$$\mu_{M_a} = \frac{H_{up}\gamma H (rS)^2}{12m} \tan \alpha^2$$

$$\sigma_{M_a}{}^2 = \left[\left\{\frac{\partial M_a}{\partial \varphi}\right\}_\mu\right]^2 \sigma_\varphi{}^2$$

$$\frac{\partial M_a}{\partial \varphi} = \frac{\gamma H (rS)^2}{12m} \tan \alpha^2 \left(\frac{-2\cos\varphi}{(1+\sin\varphi)^2}\right)$$

$$\mu_Z = \mu_{M_R} - \mu_{M_a}$$

$$\sigma_Z = \sqrt{\sigma_{M_R}{}^2 + \sigma_{M_a}{}^2}$$



From μ_Z and σ_Z we can calculate the Probability of Failure.

7) *Reliability in Failure mode-7 Formation of Hinge at Counterfort:* The counterfort retaining wall will fail may also due to the formation of plastic hinge at counterfort. This failure mode also attributes to one of the serious failure modes and hence the safety margin equation have been developed for this mode.

If safe $M_a < M_R$

Safety margin, $Z = M_R - M_a$

$$\mu_{M_R} = f_y A_{stc} d \left[1 - \frac{0.77 f_y A_{stc}}{bdf_{ck}}\right]$$

$$\sigma_{M_R}{}^2 = \left[\left\{\frac{\partial M_R}{\partial f_y}\right\}_\mu\right]^2 \sigma_{f_y}{}^2 + \left[\left\{\frac{\partial M_R}{\partial f_{ck}}\right\}_\mu\right]^2 \sigma_{f_{ck}}{}^2$$

$$\left\{\frac{\partial M_R}{\partial f_y}\right\}_\mu = A_{stc}\, d \left[1 - \frac{1.54 f_y A_{stc}}{bdf_{ck}}\right]$$

$$\left\{\frac{\partial M_R}{\partial f_{ck}}\right\}_\mu = \frac{0.77 f_y{}^2 A_{stc}{}^2}{b f_{ck}{}^2}$$

$$\mu_{M_a} = \frac{k_a \gamma H^3 S}{6}$$

$$\sigma_{M_a}{}^2 = \left[\left\{\frac{\partial M_a}{\partial \varphi}\right\}_\mu\right]^2 \sigma_\varphi{}^2$$

$$\frac{\partial M_a}{\partial \varphi} = \frac{\gamma H^3 S}{6}\left(\frac{-2\cos\varphi}{(1+\sin\varphi)^2}\right)$$

$$\mu_Z = \mu_{M_R} - \mu_{M_a}$$

$$\sigma_Z = \sqrt{\sigma_{M_R}{}^2 + \sigma_{M_a}{}^2}$$

From μ_Z and σ_Z we can calculate the Probability of Failure.

8) *Reliability in Failure mode -8 Connection between Counterfort and Stem Wall:* The stem wall is having a tendency to separate out the Counterfort due to backfill earth force. The counterfort retaining wall will fail May also due to the formation of plastic Yield line at the connection between the counterfort and stem wall. This failure mode also attributes to one of the serious failure modes and hence the safety margin equation have been developed for this mode.

If safe $P < R$

Safety margin, $Z = R - P$

$$R = 0.87 f_y A_{stcc}$$

$$\sigma_R{}^2 = \left[\left\{\frac{\partial R}{\partial f_y}\right\}_\mu\right]^2 \sigma_{f_y}{}^2 + \left[\left\{\frac{\partial R}{\partial f_{ck}}\right\}_\mu\right]^2 \sigma_{f_{ck}}{}^2$$

$$\left\{\frac{\partial R}{\partial f_y}\right\}_\mu = 0.87 A_{stcc}$$

$$\left\{\frac{\partial R}{\partial f_{ck}}\right\}_\mu = 0$$

$$P = k_a \gamma H S$$

$$\sigma_P{}^2 = \left[\left\{\frac{\partial P}{\partial \varphi}\right\}_\mu\right]^2 \sigma_\varphi{}^2$$

$$\left\{\frac{\partial P}{\partial \varphi}\right\}_\mu = \gamma H S\left(\frac{-2\cos\varphi}{(1+\sin\varphi)^2}\right)$$

$$\mu_Z = \mu_R - \mu_P$$

$$\sigma_Z = \sqrt{\sigma_R{}^2 + \sigma_P{}^2}$$

From μ_Z and σ_Z we can calculate the Probability of Failure.

9) *Reliability in Failure mode- 9 Connection between Counterfort and Heel Slab:* The heel slab is having a tendency to separate out the Counterfort due to backfill downward pressure. The counterfort retaining wall will fail May also due to the formation of plastic Yield line at the connection between the counterfort and heel slab. This failure mode also attributes to one of the serious failure modes and hence the safety margin equation have been developed for this mode.

If safe $P < R$

Safety margin, $Z = R - P$

$$R = 0.87 f_y A_{stch}$$

$$\sigma_R{}^2 = \left[\left\{\frac{\partial R}{\partial f_y}\right\}_\mu\right]^2 \sigma_{f_y}{}^2 + \left[\left\{\frac{\partial R}{\partial f_{ck}}\right\}_\mu\right]^2 \sigma_{f_{ck}}{}^2$$

$$\left\{\frac{\partial R}{\partial f_y}\right\}_\mu = 0.87 A_{stch}$$

$$\left\{\frac{\partial R}{\partial f_{ck}}\right\}_\mu = 0$$

$$P = H_{up} S$$

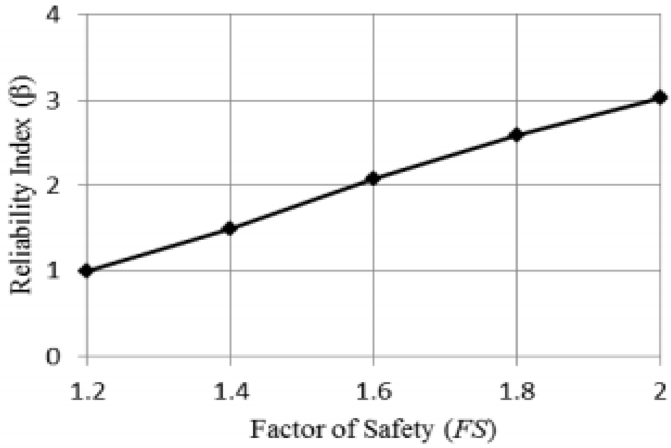
$$\sigma_P{}^2 = \left[\left\{\frac{\partial P}{\partial \varphi}\right\}_\mu\right]^2 \sigma_\varphi{}^2$$

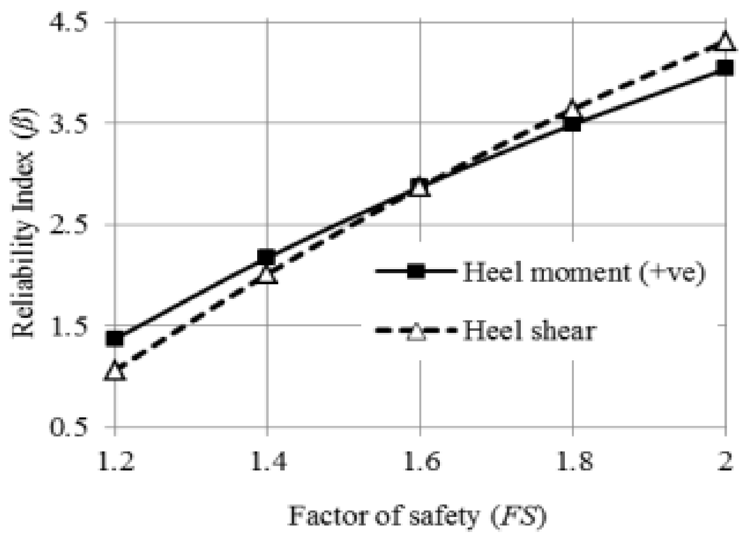
$$\left\{\frac{\partial p}{\partial \varphi}\right\}_{\mu_i} = 0$$

$$\mu_Z = \mu_R - \mu_P$$

$$\sigma_Z = \sqrt{\sigma_R{}^2 + \sigma_P{}^2}$$

From μ_Z and σ_Z we can calculate the Probability of Failure.





V. CONCLUSION

The performance of any structure is assessed by its safety, serviceability and economy. With respect to risk of life, the stuctural safety is important. For a structure to be reliable, it must perform a certain function or functions satisfactorily for which it has been designed. A limited study of system reliability of RC Counterfort retaining wall based on certain assumptions is made in this project. A MATLAB program has been written to design the RC Counterfort retaining wall as per IS 456-2000. One more program has also been written for computing the reliabilty of the designed retaining wall. The Program is made in such a way that it may suit for design and analysis of walls in different topographical conditions and by different materials. It can be extented for seismic design and as a peformance check for existing structures. When compared to the deterministic structural design, this probabilistic design will provide a structure with low probability of failure at minimum cost. Now a days, lot of retaining wall projects are going on particularly for highway projects. So it may recommend for such a works. Then we can get benefit on both safety and economy point of view.

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