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Reliability Based Design of a Berthing Structure - A Review

Tirupathi.Naidu.G¹, Balaji.K.V.G.D² and S.S.S.V.Gopala Raju³

¹Civil Engineering, Sanketika Vidya Parishad Engineering College, P.M.Palem, Visakhapatnam A.P, India.

²Civil Engineering, GITAM institute of technology, Visakhapatnam, A.P, India.

³Civil Engineering, MVGR Engineering College, A.P, India.

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ABSTRACT

A brief review of the structural reliability design methodology and its applications at system level are compiled from various sources. The main objective of this study is to present the developments in the reliability based analysis and design of land based structures, marine structures specially a diaphragm wall of a berthing structures. The present paper discusses right from the basic concepts of risk, reliability, safety and the methodologies to define reliability in a quantitative manner to aid to design a structure for a given reliability and the reliability concepts applied to aging structures, creep, shrinkage and serviceability, application of reliability analysis in other fields such as geotechnical engineering, design of marine structures, etc.,. To avoid unforeseen failure, the structural designs often undertake the concept of a safety factor to reduce the probability of failure or to increase the reliability. Analysis need to be carried out using Monte Carlo simulation assessing the partial factors, levels of risk and degree of uncertainty.

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Introduction

It is known that risk is the probability or the frequency of occurrence of a hazard or damage to infrastructure or property or environment and whereas reliability refers to the ability of a structure to perform its specified function under service conditions. Reliability can also be depicted as the probability that a structure will perform appropriately for a specified time period under a given service condition and whereas safety is referred to the relative protection from exposure to hazards. Engineering structural designs often neglect the stochastic nature of the material properties, the dimensions of the components and the externally applied load and usually consider the same by applying a factor of safety. A quantification of the uncertainty in design of structural components is necessary in critical applications like in land based, marine, space and aircraft applications.

With respect to the reliability of components, mean life of a part or component refers to the average life a specified number of components which is measured over the entire span of their life. The mean time to failure (MTTF) refers to the sum of survival time (up time) for all the components put under utility divided by the number of components, which are failed. System Reliability is the overall reliability of a structure or any system will be governed by the reliability of the individual components. If the components are so arranged that the failure of any component will lead to the total failure in the system, the same is envisaged to be in series.

Review

The present review presents information of such investigations that provide insight to the effect of reliability based design applied to different issues in the field of civil engineering.

Glen H. Lemon, et al.,(1974), presented a brief overview of the structural reliability problem and its relationship to probabilistic and statistical concepts and compiled selected

references on structural reliability from various sources including references address with implementing the structural reliability approach.

The study of the dynamic response of offshore towers to wind-generated random ocean waves is presented (C. Poliou, et al., 1987), the analysis is performed in the frequency domain and the equations of motion are solved using equivalent linearization techniques. In this study, two methods of reliability analysis are considered 1.a statistical fatigue damage analysis using the American Welding Society model (high-cycle fatigue analysis) to demonstrate the influence of the design stress level for fatigue-critical members on the fatigue reliability and a first-passage failure probability with periodic inspections and 2.A crack growth analysis is performed using the fracture mechanics method to estimate propagated crack size and corresponding residual strength under random service loading conditions. The effect of periodic inspections is very important if a fatigue crack already exists. It is also shown that there is always a limit in the number of inspections beyond which no significant improvement can be achieved.

The Structural reliability methodology and its application at the system level(G.E. Ingram, et al.,1978) , briefly discusses the use of structural reliability methodology for general systems reliability analyses, previous applications of this approach to several different types of systems. A description of the basic methodology is given followed by a discussion of the computational processes that are available for arriving at solutions. The basic structural reliability approach involves defining first the "requirements" (or stresses) to which a structure will be subjected in terms of the static and dynamic loadings and other environments, such as temperature and pressure. Secondly, the "capability" (or strength) of the structure to withstand the requirements (stresses) must be defined in terms of the appropriate structural parameters, such as static and dynamic material properties, and structural dimensions and

Tele:

E-mail addresses: gtpnaaidu@gmail.com

configuration. Since, in general, the structural dimensions, configuration, loadings, and other environments are random variables, the capability and requirements are also random variables. Therefore, the reliability of the structure is the probability that the requirements imposed upon the structure do not exceed the capability of the structure to withstand them within a time period of interest. There are basically three computational procedures for generating solutions of this type of problem: (1) closed form solution, (2) Monte Carlo simulation, and (3) numerical techniques. This paper suggests that the optimal procedure is a combination of these three, depending upon the particular problem.

During the seventies, second moment structural reliability analysis was extensively discussed with respect to philosophy and method (O. Detlevsen, 1982), recent clarification into a consistent formalism represented by the extended second moment reliability theory with the generalized reliability index as its measure of safety. Its methods of formal failure probability calculations are useful independent of the opinion that one may adopt about the philosophy of the second moment reliability formalism.

The structural Reliability Analysis of chain-like series structural systems was performed for the special cases of lognormal stress and both Weibull and lognormal component strength (Lidvin Kjerengtroen, et al., 1984) and to relate component reliability to system reliability. It has application to establishment of design requirements, e.g. for fatigue avoidance in tethering components for marine structures or disks for turbine engines, when the events of failure of each member in a series system are assumed to be mutually independent, a simple expression for risk results. But component failure events are not independent, because of the presence of the same stress term in each event. Correction factors to be applied to the simple expression are derived for the stress and strength distributions considered. The conservative assumption of independent component failure events can produce weight penalties of 10% or more, is provided which illustrates application of the results to establish a design requirement for a tendon of a tension leg platform.

The current version of ACI Standard 318 on reinforced concrete design uses an overall resistance factor on structural action to account for uncertainty in the resistance variables for which formulated reliability based code for reinforced concrete buildings (Morris Israel, et al., 1987). The partial resistance factors also may be used to address the different sources of variability directly; such a format may be advantageous for reinforced concrete. First-order, second-moment reliability analysis methods are used to develop partial resistance factors that are compatible with the load requirements of ANSI Standard A58.1-1982. Flexure, compression plus bending, and shear limit states are analyzed. The consistency of reliabilities afforded by alternate resistance factor formats is compared, and the performance from a reliability viewpoint of certain key code provisions is investigated.

The study to develop a general method for estimating the system reliability of offshore structures with the aid of the full distribution method and to introduce a probabilistic definition of structural redundancy (C. Paliou, et al., 1990). Structures are treated as systems of structural components, failure of any number of these components results in a redistribution of the internal and/or external forces. The probability of structural failure is then evaluated by examining a limited number of significant sequences of member failures that produce collapse of the structure. The structure examined is an indeterminate deep

off shore truss under fully developed sea conditions. Two different types of material behavior are considered to characterize the type of failure of the components: ductile and brittle behaviors. This reliability analysis and redundancy definition will form an important analytical basis for further investigation of offshore structural integrity.

A general strategy for estimating the failure probability of the class of structural systems for which each deterministic structural analysis is expensive is proposed (Yaacob Ibrahim, 1991) and the strategy is interactive, sequential, and iterative. The study relies upon the user to interpret and generate information about the system through the use of appropriate techniques such as directed experimental design, sampling techniques, response surface, and first- and second-order reliability methods. In the strategy, one tries to obtain increasingly accurate representations of the more important failure regions and use these representations to arrive at an estimate of the system failure probability. The goal is to obtain an estimate with the minimum number of structural analyses. There are no concrete steps in the strategy and the steps taken for each problem are decided by the user. The strategy was applied to two examples, the first example, which is a simple truss structure with brittle components subjected to a static load, is to demonstrate the strategy in greater detail and in the second example, a first estimate of the probability of failure of an offshore structure was obtained using the strategy.

Classical reliability has significantly enhanced the ability of engineers to assess the safety of constructed projects (Karen C. Chou, et al., 1993), Bayes' theorem is an effective tool in updating prior probabilities when the value of a random parameter is known. The theorem fails to adequately address the uncertainties of the subjective parameters, that are associated with structural evaluation. It has been demonstrated that these parameters can be significant to the overall safety assessment. With the introduction of fuzzy-set theory, it is possible to quantify the qualitative evaluation and incorporate it into the safety assessment. An algorithm to compute the posterior probability based on visual inspection of structural components by incorporating fuzzy-set theory into Bayes' theorem. The results based on two examples one a reinforced concrete beam and two a structural frame, showed that the fuzzy-Bayesian approach is a viable enhancement to the safety assessment of existing structures.

A methodology is presented for quantifying the uncertainty in the strength measures and the analytical models used to develop reliability-based design formats for marine structures, the uncertainties associated with the strength side of the various limit-states need to be investigated (White.G.J. et al., 1993). Existing design codes in other fields of engineering are reviewed for limit-state expressions and measures of uncertainty in modeling, one of the limit-states is chosen as an approach for determining the level of uncertainty associated with the strength parameters and the analytical model.

A probabilistic model is developed to estimate immediate, creep, and shrinkage deflections (Mark G. Stewart, 1996), Monte Carlo simulation is used to estimate deflections and probabilities of serviceability failure (lifetime and for each 8 yr tenancy) for reinforced concrete beams sized according to the span-to-depth ratio serviceability requirements of Australian, British, and American Concrete Structures Codes. Serviceability failure is defined to occur when a deflection exceeds an allowable deflection limit as a result of flexure. It was found that the span-to-depth ratio serviceability requirements of these codes produce significantly different serviceability reliabilities.

This is probably a consequence of the fact that the serviceability specifications of these codes have not been subjected to code calibration. A code-calibration exercise considering load factors, loading combinations, and/or allowable deflection limits may minimize these variations in serviceability reliabilities.

First- and second-order reliability methods are generally considered to be among the most useful for computing structural reliability (Yan-Gang Zhao, et al., 2000). In these methods, the uncertainties included in resistances and loads are generally expressed as continuous random variables that have a known cumulative distribution function. The Rosenblatt transformation is a fundamental requirement for structural reliability analysis. However, in practical applications, the cumulative distribution functions of some random variables are unknown, and the probabilistic characteristics of these variables may be expressed using only statistical moments. In the present study, a structural reliability analysis method with inclusion of random variables with unknown cumulative distribution functions is suggested. Normal transformation methods that make use of high-order moments are investigated, and an accurate third-moment standardization function is proposed. Using the proposed method, the normal transformation for random variables with unknown cumulative distribution functions can be realized without using the Rosenblatt transformation. Through the numerical examples presented, the proposed method is found to be sufficiently accurate to include the random variables with unknown cumulative distribution functions in the first- and second-order reliability analyses with little extra computational effort.

Approximation methods such as the response surface method (RSM) are widely used to alleviate the computational burden of engineering analyses (Irfankaymaz et al., 2005). For reliability analysis, the common approach in the RSM is to use regression methods based on least square methods. However, for structural reliability problems, RSMs should approximate the performance function around the design point where its value is close to zero. Therefore, in this study, a new response surface called ADAPRES is proposed, in which a weighted regression method is applied in place of normal regression. The experimental points are also selected from the region where the design point is most likely to exist. Examples are given to demonstrate the benefit of the proposed method for both numerical and implicit performance functions.

The use of probability theory in reliability based optimum design of reinforced gravity retaining wall is described. The formulation for computing system reliability index is presented. A parametric study is conducted using advanced first order second moment method (AFOSM) developed by Hasofer-Lind and Rackwitz-Fiessler (HL-RF) to assess the effect of uncertainties in design parameters on the probability of failure of reinforced gravity retaining wall. Totally 8 modes of failure are considered, viz overturning, sliding, eccentricity, bearing capacity failure, shear and moment failure in the toe slab and heel slab. The analysis is performed by treating back fill soil properties, foundation soil properties, geometric properties of wall, reinforcement properties and concrete properties as random variables. These results are used to investigate optimum wall proportions for different coefficients of variation of ϕ (5% and 10%) and targeting system reliability index (β_i) in the range of 3 – 3.2.

Modern geotechnical design codes are migrating towards Load and Resistance Factor Design (LRFD) methodologies (Gordon A. Fenton, et al., 2007), the Danish geotechnical code has been based on LRFD for several decades, but more recently

the Eurocode and the Australian Standards have turned in this direction. Where the geotechnical system supports a structure, the load factors are generally determined by the structural codes. The geotechnical resistance factors, typically determined by calibration with traditional working stress (or allowable stress) design, have yet to be clearly defined in geotechnical design codes. Research into the reliability of geotechnical systems is needed in order for resistance factors to be determined. This paper presents the results of a preliminary study into the effect of a soil's spatial variability on the settlement and ultimate load statistics of a pile. The results are used to provide recommendations on approaches to reliability-based deep foundation design at the serviceability and ultimate limit states.

A method is proposed for developing renewal criteria for marine structures based on the reliability approach, it accounts for structures' degradation over time and uncertainties of loads (Lyuben D. Ivanov, et al., 2007). Thus, the implied risk in geometry-based renewal criteria for marine structures can be revealed. The governing failure mode is first determined, and then the time-variant reliability of the structure is calculated. Then, the probability of exceeding given permissible limits in geometry-based renewal criteria is calculated for any year of the ship's age or for any time period. Combining the two types of calculations, conditions are obtained for when the control of the geometric properties truly represents the control of the structural reliability. An example is given for vertically corrugated bulkheads used in tankers, but the method is general and can be applied to any structural component or marine structure as a whole. The method presented by the authors allows for evaluating the effect of corrosion protection with the risk that the example corrugated structure will exceed given permissible limits over time. The methodology can be used in the optimization process in the early design stage as a predictive tool or during operation.

Using elementary engineering mechanics, a simple boom structure is analysed and its reliability is assessed (P.J Laumakis et al., 2010). It is assumed that four of the structural variables are random with a known joint probability distribution function. From the structural analysis, an explicit expression for failure is obtained. The reliability of the structure is computed analytically from first principles of probability theory. Additionally, it is shown that Monte-Carlo simulation can be implemented more readily with results that compare favourably to the theoretical calculations. Thus, the power and utility of Monte-Carlo simulation are demonstrated. Specifically, the boom is analysed for different probability distribution functions for the underlying components. The analytical and numerical analysis contained in this application are appropriate for any upper level undergraduate course in applied mathematics, scientific computation or engineering reliability where the Monte-Carlo method is being studied.

Several reliability analyses of a sheet pile wall in a marine environment were performed, in which the influence of a wide range of corrosion models on its safety was assessed (Osorio.P. et al., 2011). The First Order Reliability Method (FORM) was used and the reliability analyses were performed using a combination of different programs. The effect that the variation of the coefficient of variation (CoV) of the probability distributions has on the measured level of safety is not linear. For certain ranges of CoV, the influence on the safety level is not very significant, whereas in other ranges it causes an abrupt reduction of the safety, meaning that the access to good quality data of thickness loss due to corrosion- is important to avoid erroneous conclusions about the safety. A design procedure to

include the effect of corrosion in the safety of the structure was also developed.

Uncertainties in the geotechnical design variables and design equations have a significant impact on the safety of cantilever retaining walls (**T.Goh, et.al., 2011**), traditionally, uncertainties in the geotechnical design are addressed by incorporating a conservative factor of safety in the analytical model. In this paper, a risk-based approach is adopted to assess the influence of the geotechnical variable and design equation uncertainties on the design of cantilever retaining walls in sand using the “partial factor of safety on shear strength” approach. A random model factor based on large-scale laboratory test data from the literature has been incorporated into the reliability analyses to quantify the uncertainty in the geotechnical calculation model. Analyses conducted using Monte Carlo simulation show that the same partial factor can have very different levels of risk depending on the degree of uncertainty of the mean value of the soil friction angle. Calibration studies show the partial factor necessary to achieve target probability values of 1 and 0.1%.

For the parameter sensitivity estimation with implicit limit state functions in the time-invariant reliability analysis (**W.Zhao, et.al., 2011**), the common Monte Carlo simulation based approach involves multiple trials for each parameter being varied, which will increase associated computational cost and the cost may become inevitably high especially when many random variables are involved. Another effective approach for this problem is featured as constructing the equivalent limit state function (usually called response surface) and performing the estimation in FORM/SORM. However, as the equivalent limit state function is polynomial in the traditional response surface method, it is not a good approximation especially for some highly non-linear limit state functions. To solve the above two problems, a new method, support vector regression based response surface method, is therefore presented in this paper. The support vector regression algorithm is employed to construct the equivalent limit state function and FORM/SORM is used in the parameter sensitivity estimation, and then two illustrative examples are given. It is shown that the computational cost of the sensitivity estimation can be greatly reduced and the accuracy can be retained, and results of the sensitivity estimation obtained by the proposed method are in satisfactory agreement with those computed by the conventional Monte Carlo methods.

For Civil and Environmental Engineering curriculum a stand-alone introductory course called Engineering Risk Analysis introduces concepts of reliability analysis (**Robb Eric.S.Moss, 2011**), encompasses all the sub-disciplines in civil and environmental engineering. After five years of teaching this course there are a number of lessons that may be useful to other instructors including; solving a simple example problem using multiple methods, focusing on the normal and lognormal distributions for a quick preliminary solution, using reliability spreadsheet solutions, and allowing the students to develop their own applications of probabilistic tools. A discussion of the course format, references and resources, pedagogy devices, and in- class examples are covered. The higher goal of this course is to educate students in probabilistic methods, familiarize them with risk analysis procedures, and to elevate the basic level of understanding of uncertainty in engineering and how to properly deal with it.

In case of reliability analysis of a complex engineering structures a very large number of system parameters can be considered to be random variables (**Sondipon Adhikari, 2012**).

The difficulty in computing the failure probability increases rapidly with the number of variables. In this paper, a few methods are proposed whereby the number of variables can be reduced without compromising the accuracy of the reliability calculation. Based on the sensitivity of the failure surface, three new reduction methods, namely (a) gradient iteration method, (b) dominant gradient method, and (c) relative importance variable method, have been proposed with numerical examples to illustrate the proposed methods. Keywords Reliability analysis-optimization-approximation methods-FORM-SORM

Geotechnical design often involves high, hard-to-control parameter uncertainties, which result in high variability in the system response (**C.HseinJuang, et.al., 2013**). The variability in system response, which is typically addressed by satisfying a minimum safety measure in the form of a factor of safety or reliability index, forces the geotechnical designer to compromise between safety and efficiency (i.e., cost). When robustness of the geotechnical design against such system response variability is not evaluated during the design process, the tradeoff between over-design for safety and under-design for cost-savings is exacerbated. This paper introduces a novel design approach, Reliability-based Robust Design Optimization that considers explicitly the reliability, robustness, and cost. This design methodology is demonstrated with the design of a cantilever retaining wall. System reliability index is used as the performance measure and the tradeoff among the computed reliability index, the variance of the reliability index (as a measure of the robustness), and the cost are investigated. The results show that for some designs (with reliability index between 3 and 3.65), no tradeoff exists between the reliability index and its variance; hence, the design with the greatest reliability index also has the highest robustness (smallest variance) for a given cost. For other designs, a tradeoff relationship exists between the reliability index and its variance for a given cost.

A rational approach to uncertainties in geotechnical design is reliability-based design (RBD) and a readily useable form is load resistance factor design (LRFD) (**Tien H .Wu, 2013**). In LRFD, load and resistance factors are used to obtain an acceptable level of reliability or failure probability. This paper reviews the development of reliability-based design and the various uncertainties that control the resistance factor. These include uncertainties about material models, analytical models, and methods for reliability assessment. Data available from various sources are compared. The estimated uncertainties are compared with observed performance from case histories and current design codes. Implications on use of LRFD in practice are suggested. Uncertainty about the load is not considered here because an extensive literature already exists.

For excavations in built-up areas with deep deposits of soft clays, it is essential to control ground movements to minimize damage to adjacent structures and facilities (**Anthony T.C. et.al., 2013**). This is commonly carried out by controlling the deflections of the retaining wall system. The limiting wall deflection or serviceability limit state is typically taken to be a percentage of the excavation height. In this study, extensive plane strain finite element analyses have been carried out to examine the excavation-induced wall deflections for a deep deposit of soft clay supported by diaphragm walls and bracing. Based on the numerical results, two polynomial regression approaches were used to develop the equations for estimating the maximum wall deflection. This paper describes how the developed equations can be used to perform reliability analysis

of the diaphragm wall serviceability limit state to estimate the probability of exceeding the limiting wall deflection.

The paper presents an efficient third-moment saddlepoint approximation approach for probabilistic uncertainty analysis and reliability evaluation of random structures (Shuxiang Guo, 2014). By constructing a concise cumulant generating function (CGF) for the state variable according to its first three statistical moments, approximate probability density function and cumulative distribution function of the state variable, which may possess any types of distribution, are obtained analytically by using saddlepoint approximation technique. A convenient generalized procedure for structural reliability analysis is then presented. In the procedure, the simplicity of general moment matching method and the accuracy of saddlepoint approximation technique are integrated effectively. The main difference of the presented method from existing moment methods is that the presented method may provide more detailed information about the distribution of the state variable. The main difference of the presented method from existing saddlepoint approximation techniques is that it does not strictly require the existence of the CGFs of input random variables. With the advantages, the presented method is more convenient and can be used for reliability evaluation of uncertain structures where the concrete probability distributions of input random variables are known or unknown. It is illustrated and examined by five representative examples that the presented method is effective and feasible.

Conclusions:

- There is a need to study the uncertainties in the geotechnical design, the variables and design equations have a significant impact on the safety of cantilever diaphragm walls of a berthing structure since the failure of a structure in a port can be a major issue of national interest and economic loss.
- Uncertainties in the geotechnical design need to be addressed by incorporating an appropriate factor of safety in the analytical model.
- A risk-based approach need to be adopted to assess the influence of the geotechnical variable and design equation uncertainties on the design of cantilever diaphragm walls of berthing structure in marine soils consists of marine clay and fine sand using the “partial factor of safety on shear strength” approach.
- It is required to incorporate a random model factor based on large-scale laboratory test data from the field (literature) into the reliability analyses to quantify the uncertainty in the geotechnical calculation model.
- Analysis need to be carried out using Monte Carlo simulation assessing the partial factors, levels of risk and degree of uncertainty of the mean values of the soil friction angle and cohesion.
- The Calibration studies have to be carried to arrive at the partial factor necessary to achieve target probability values.

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