ICOSSAR '89

5th International Conference on
Structural Safety and Reliability

Reprinted from Structural Safety & Reliability
Proceedings of ICOSSAR '89/5th Int'l. Conf.
San Francisco, CA/August 7-11, 1989

APPLICATION OF PROBABILISTIC METHODS IN CONSTRUCTION INDUSTRY

Kiyoshi Ishii*, Makoto Suzuki* and Fumio Yamazaki**

* Ohsaki Research Institute, Shimizu Corporation, 2-2-2 Uchisaiwai-cho, Chiyoda-ku, Tokyo 100, Japan.
**Institute of Industrial Science University of Tokyo, 7-22-1 Roppongi, Minato-ku, Tokyo 106, Japan

ABSTRACT

Recent attempts for theoretical development and engineering application of probabilistic methods, which have been carried out in a Japanese engineering and construction company, are summarized. The first part of the paper describes analytical and numerical tools developed for evaluating structural safety and reliability, especially related to stochastic field theory and stochastic finite element analysis. In the second part, numerical results are demonstrated as practical applications of such probabilistic methods. The examples cover the reliability analyses of various types of structures, the optimum design, and the trade-off between cost and safety. Although these attempts are still preliminary, they will play an important role to rationalize the structural design procedures and the decision making in construction near future.

KEYWORDS

Construction industry, probabilistic methods, structural safety, finite element analysis, Monte Carlo method, structural design, economy.

1. INTRODUCTION

Recently, probabilistic methods have attracted considerable attention in planning, design and construction stages of civil engineering structures. Along this line, major Japanese engineering and construction companies have devoted to research and development of probabilistic analysis methods as well as their practical applications, since they have extensive research personnel and facilities including powerful computer softwares and hardwares. This paper describes one of such attempts which has been conducted by Ohsaki Research Institute, Shimizu Corporation.

In last several years, we have carried out intensive studies for developing analytical and numerical tools of evaluating structural safety and reliability. Especially, we focused ourselves on several hot topics: e.g., stochastic finite element analysis, simulation techniques of stochastic fields, system identification techniques, and Kalman filter techniques. A brief explanation of these theoretical development and verification study is given in section 2.

These elaborate stochastic methods and other existing techniques are applied to the evaluation of design alternatives, the feasibility study of large-scale structures as well as the reliability analysis of existing structures. Such examples are as follows: optimum design of drainage pipes, evaluation of design alternatives for structures under construction, reliability analysis of reinforcement joints, trade-offs between safety and economy of offshore structures, reliability analysis of oil tank foundations, and reliability analysis of ground supporting a building. These applications are described in section 3.

It is noted that in creating these examples, a number of computer codes have been developed and they have been executed mostly on FACOM M380Q main frame computer. Personal computers (e.g., IBM 5550) have been also employed for several cases.

2. DEVELOPMENT OF ANALYTICAL AND NUMERICAL TOOLS

Stochastic Finite Element Method by First-order Approximation [1]

A stochastic finite element method for reliability analysis is developed based on the first-order approximation. The Taylor series expansion about a failure point is performed iteratively until the safety index β converges. The method incorporates the equivalent normal representation of non-Gaussian random variables and offers two advantages; it gives a consistent measure of the limit state probability defined in terms of different but equivalent formulations of performance function; and it can be applied to reliability analysis including non-Gaussian random variables. Numerical results using this method are favorably compared with those by Monte Carlo simulation for a simple model. Furthermore, this method is applied to stability analysis of earth slopes including material property variations (Fig. 1), and the limit state probabilities are evaluated for local and global failures.

Neumann Expansion for Stochastic Finite Element Analysis [2]

This study deals with the problem of structural response variability resulting from the spatial variability of material properties of structures under static loads. The Neumann expansion technique is employed in deriving the finite element solution for the response variability within the framework of Monte Carlo simulation (MCS). Since the stiffness matrix factorization is required only once for all the sample structures,

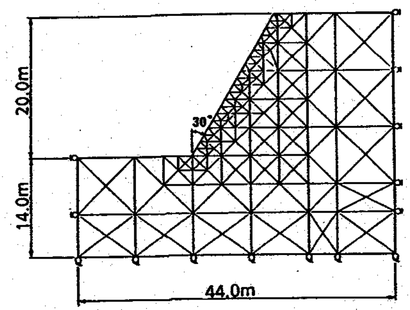

Fig. 1 Finite Element Model for Slope Stability Analysis

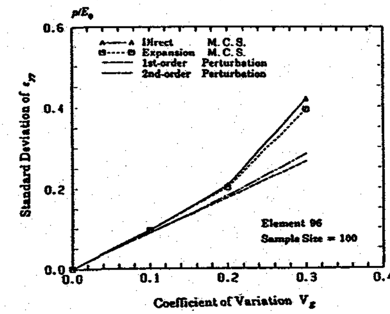

Fig. 2 Comparison of Standard Deviation of Strain by Various Methods

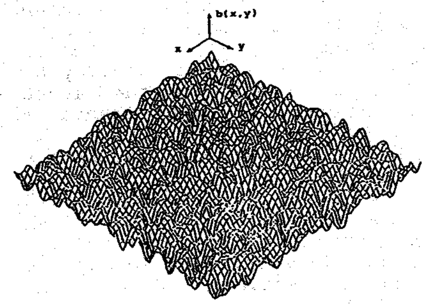

Fig. 3 Simulated Non-Gaussian Stochastic Field

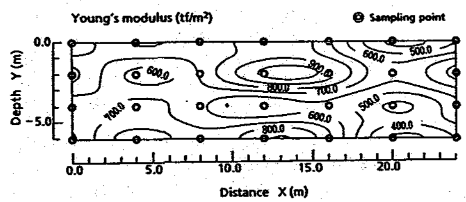

Fig. 4 Estimated Young's Modulus Variation by Kriging Technique

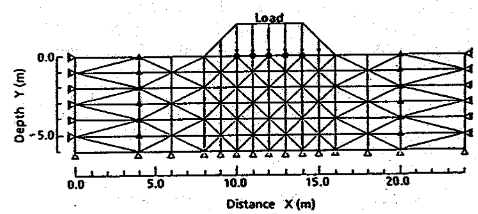

Fig. 5 Finite Element Model for Settlement Analysis using Extended Kalman Filter

the MCS method based on Neumann expansion is computationally much more efficient than the direct MCS method where the sample stiffness is factorized each time.

The numerical results from such Monte Carlo methods are also compared with those obtained by the first- and second-order perturbation methods with respect to accuracy, convergence, and computational efficiency (Fig. 2). The comparison shows that the validity of the perturbation methods is limited to the cases where the material property variation has a relatively small coefficient of variation, particularly when Young's modulus itself is assumed to form a stochastic field.

Digital Generation of Non-Gaussian Stochastic Fields [3]

A method of digitally generating sample functions of multi-dimensional non-Gaussian homogeneous stochastic fields is developed when the target spectral density function and the target probability distribution function are given. First sample functions of the Gaussian stochastic field are generated so as to reproduce the target spectral density function of the non-Gaussian field. These sample functions are mapped into the sample functions of non-Gaussian field on the probability distribution function diagram. Through this operation, the spectral density of the resulting non-Gaussian field will be different from the target while the mean and variance are unchanged. Thus an iterative scheme updating the spectral density is introduced to satisfy both the target spectral density and probability distribution functions.

A numerical example is worked out for a two-dimensional stochastic field which has a beta distribution (Fig. 3). After three iterations, the sample function closely reproduced the prescribed beta distribution and spectral density. The method may have a wide range of applicability to engineering problems involving stochastic fields where the Gaussian assumption is not appropriate.

A Kriging Technique for Stochastic Spatial Interpolation [4]

When a reliability analysis for geotechnical problems is performed based on the stochastic finite element method, a proper estimation of spatial variation of soil properties is important. To give a best linear unbiased estimator of an unknown space parameter, a Kriging technique is incorporated for stochastic spatial interpolation. The Kriging technique enables us to estimate the spatial variation of a soil parameter, e.g., Young's modulus, with fully utilizing the observed data (Fig. 4). The applicability of this approach to the first-order stochastic finite element analysis is investigated and the numerical results are compared with those obtained by the conditional simulation technique.

An Extended Kalman Filter Technique for Back Analysis [5]

The finite element method has been a successful analytical tool in solving various geotechnical engineering problems such as a prediction of settlement (Fig. 5). Accuracy of the finite element analysis, however, depends mostly on accurate estimation of soil properties, while reliable soil properties cannot always be obtained easily. Hence, an extended Kalman filter, a numerical technique developed in the field of system identification, is

introduced in this study for soil parameter estimation. With the aid of the finite element technique, spatially variable soil properties are estimated from the observed displacement values. This back analysis method may have wide applicability in various fields of civil engineering.

3. APPLICATIONS IN STRUCTURAL DESIGN AND ANALYSIS

Optimum Design of Drainage Pipes for Slope Stability [6]

A reliability-based procedure for selecting a countermeasure against a slope failure is performed. The type of failure considered in this study is a sliding slope failure due to ground water flow during a dry-up operation of the graving dock (Fig. 6). A proposed countermeasure consists of a series of horizontal drainage pipes. The optimum design is selected among relevant alternatives with various horizontal drainage pipe spacings. A widely accepted criterion for the decision is the minimum expected cost, which directly incorporates quantitative evaluation of safety in terms of the failure probability.

Design Alternatives of Structures under Construction [7]

This study performs a safety evaluation of design alternatives for structures under construction from a view point of economical aspects. In this evaluation, a construction period is divided into several terms corresponding to the construction stages and several possible failure modes are considered for each term. The magnitudes of loads are statistically estimated by the extreme value distribution. The delay or the additional expense due to a failure is intuitively estimated by engineers for each damage level in each construction stage. The estimates are based on a number of parameters evaluated synthetically, in which the total anticipated expense and the additional expense required to recover from the damage are included. The proposed evaluation method has been applied to an actual harbor construction project and its applicability and efficiency are demonstrated (Fig. 7).

Reliability Analysis of Reinforcement Joints [8]

In order to construct LNG inground tanks, underground walls made of reinforced concrete are used for an earth retaining wall (Fig. 8). The length of reinforcement splices of wall segments is requiered to be longer than that for ordinary construction because concrete is placed into slurry. However, the long splice reduces workability. To cope with this construction problem, a reliability analysis is introduced to determine a proper splice length. The variation of material property values are estimated by statistical analysis. The point estimate method is employed to evaluate the failure probability in both the vertical and circular directions assuming that the unit weight and Young's modulus of soil, and the strengths of concrete and steel are random variables. In this reliability analysis, the effect of improvement on workability by reducing the splice length is considered. Then, the splice length of 45ϕ (ϕ = the diameter of reinforcement), which is required for the deterministic design, is reduced to 25ϕ still maintaining the adequate safety margin.

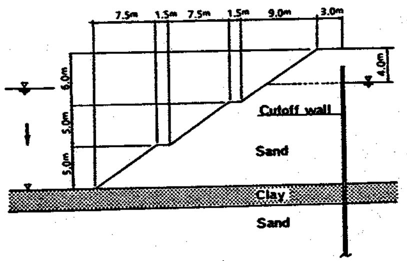

Fig. 6 Section of Graving Dry Dock for Optimum Design of Drainage Pipes

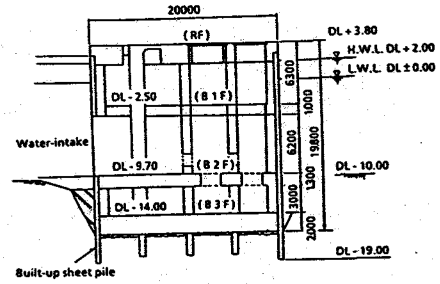

Fig. 7 Section of Pump House for Design Alternative Study

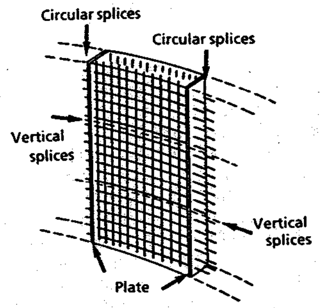

Fig. 8 Reinforcement Splices of Earth Retaining Wall Segmant

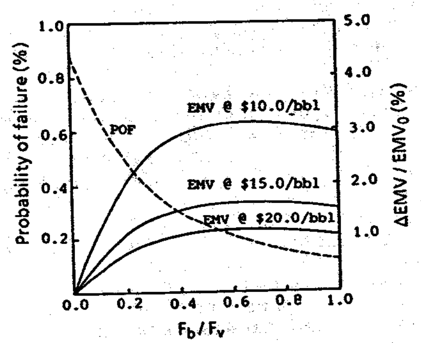

Fig. 9 Probability of Failure (POF) and Expected Monetary Value (EMV)

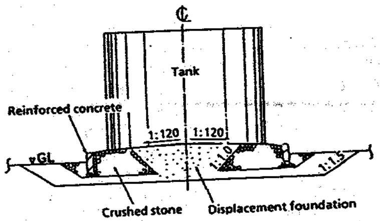

Fig. 10 Oil Tank Foundation for Reliability Analysis

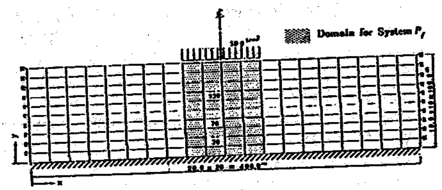

Fig. 11 Finite Element Model of Ground under Vertical Load

Trade-off between Safety and Economy of Offshore Structure [9]

This study describes the most fundamental reliability design approach and the analysis to evaluate the trade-off between two prominent design goals: safety and economy. The reliability analysis and trade-off analysis are carried out for the sliding failure mode of a gravity-type offshore platform subjected to seismic loading. The reliability of a structural system can be assessed by defining the performance function, statistical parameters that are based on several rather crude assumptions in order to simplify the study. However the emphases are placed on studying the following items of interest: ① clarify the reliability aspects in the existing LSD codes (DnV, NBS) and compare the results using a simple example, ② perform the expected monetary value analysis for various failure probabilities (Fig. 9). The monetary value was expressed in terms of the net present worth of the profit considering the initial investment including the varying ballasting cost for improved stability and the annual costs for undamaged and damaged states. The effect of varying oil price was also examined in the revenue side of the analysis.

Reliability Analysis of Oil Tank Foundations [10]

When oil tank foundations of gravity type are to be constructed, analyses for settlement, bearing capacity and liquefaction must be performed (Fig. 10). First, if the supporting soil is found not to satisfy these criteria, the soil improvement must be considered. The probability to exceed a serviceable limit settlement is obtained using the first-order approximation method. Then, their analyses results are compared with those from the measurement, and they are in good agreement. Next, the expected monetary value analysis for liquefaction risk is performed for the time spans of 1, 20 and 50 years. A damage cost is assumed to be 10 times of the initial cost if an oil tank is collapsed. The relationship between the expected monetary value and the serviceable period may be useful in the decision making for soil improvement.

Reliability Analysis of Ground Supporting A Building [11]

A diluvial gravel ground is recently considered as a future possible location for nuclear facilities in Japan. In this study, a safety analysis of the ground, modeled by finite elements (Fig. 11), subjected to a dead load of a power plant building is carried out considering spatial variation of soil properties.

First, the internal friction angle ϕ of soil is assumed to follow a log-normal distribution with an anisotropic spatial auto-correlation function. This example including a uni-variate stochastic field reveals the accuracy of Monte Carlo simulation and Monte Carlo integration methods when the number of random variables becomes large. Secondly, both the strength parameter ϕ and Poisson's ratio ν are considered to be spatially random. This bi-variate field problem shows that the degree of cross-correlation has a significant influence on the limit state probability as well as the correlation distance. Hence the importance of the stochastic modeling is pointed out.

4. CONCLUDING REMARKS

This paper summarizes recent studies related to structural safety and reliability performed at a Japanese engineering and construction company. First, analytical and numerical tools which we have developed based on the state-of-the-art of probabilistic methods are presented. Emphasis is placed on stochastic field and stochastic finite element analysis. Secondly, practical applications of such probabilistic methods are demonstrated. The examples cover the reliability analyses of various types of structures using various existing and newly developed techniques.

In the several examples, economical aspects are also considered along with safety aspects. Total costs of structures during their life span including construction, operation and maintenance must be taken into consideration in the assessment of design alternatives.

Although these attempts are still preliminary, we expect the probabilistic methods will play an important role in these various issues encountered in the construction industry near future.

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