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Reliability and Stability Assessment of Concrete Gravity Structures (RCSLIDE): Theoretical Manual

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Prepared for Headquarters, U.S. Army Corps of Engineers

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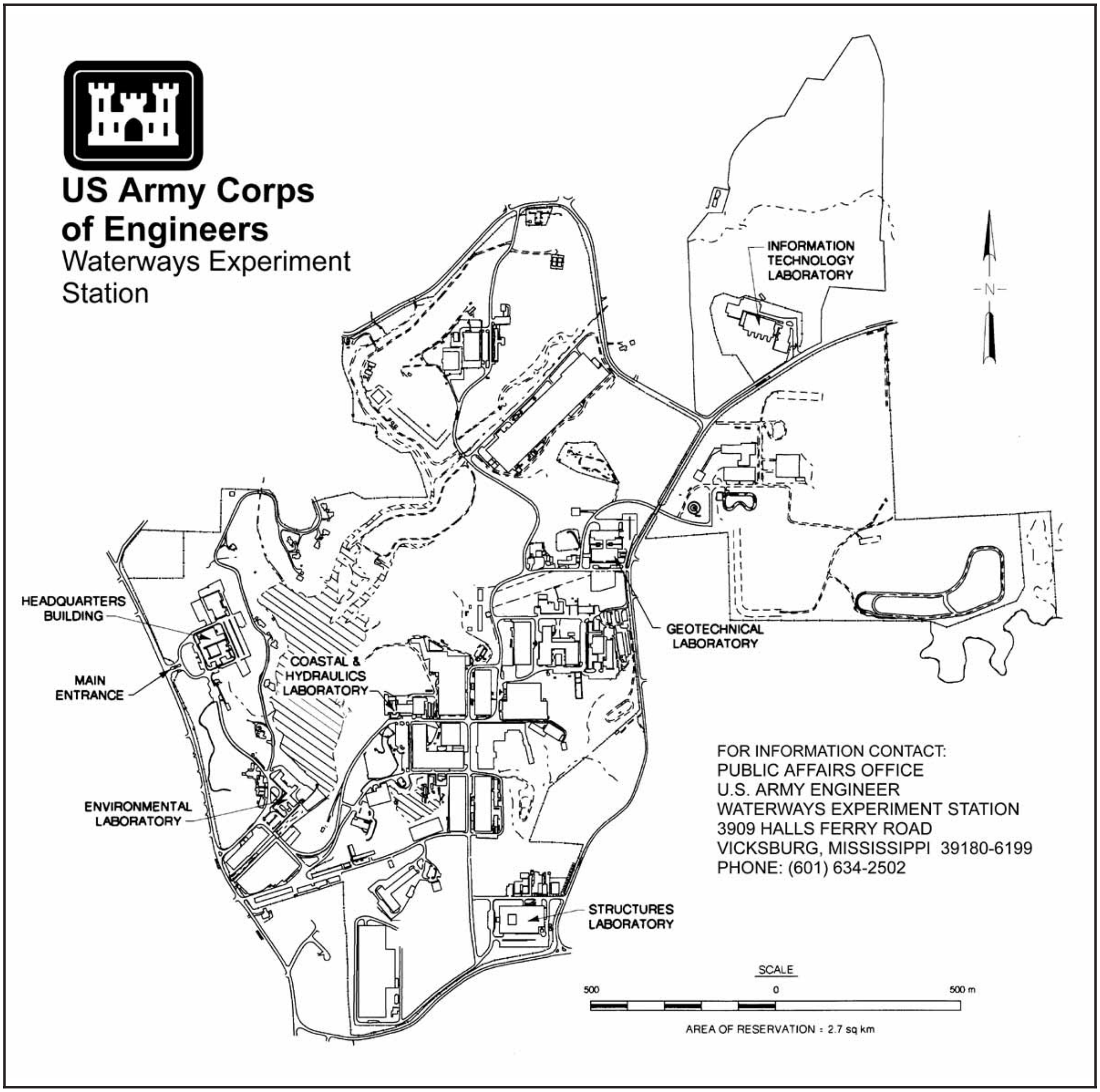

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Preface

The work reported herein was funded under the Risk Analysis for Water Resources Investments Research and Development Program at the U.S. Army Engineer Waterways Experiment Station (WES). It was performed by Drs. Bilal M. Ayyub and Ru-Jen Chao of BMA Engineering, Inc., under Contract Nos. DACW-39-95-K0026 and DACW-39-95-K0046 with assistance and guidance from Dr. Mary Ann Leggett and Mr. Robert C. Patev, Computer-Aided Engineering Division (CAED), Information Technology Laboratory (ITL), WES. Publication of this report was funded by the Computer Aided Structural Engineering (CASE) project. The work was coordinated with Headquarters, U.S. Army Corps of Engineers (HQUSACE), by Messrs. Jerry Foster and Don Dressler of the Engineering Division, Directorate of Civil Works. The work was performed under the general supervision of Mr. H. Wayne Jones, Chief, CAED, and Dr. N. Radhakrishnan, Director, ITL.

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1 Introduction

Objectives and Scope

Current safety analysis procedures and computer programs such as CSLIDE (Pace and Noddin 1987) for concrete retaining walls and gravity structures compute traditional safety factors that are not based on reliability analysis. CSLIDE defines the safety factor as the ratio of sliding resistance to sliding force. Safety factors are not accurate measures of stability reliability because they do not account for the various uncertainties in underlying parameters or variables of stability problems. Also, the factors of safety do not convey the nonlinear nature of relationships between the margin of safety that they measure and the unsatisfactory performance likelihood that can be used as a basis for measuring stability reliability.

The objective of this study was to develop reliability assessment methods for the stability of gravity concrete structures. This report describes the probability-based reliability assessment methodology for concrete retaining walls and gravity structures that was developed. The methodology is based on the U.S. Army Corps of Engineers Computer-Aided Structural Engineering (CASE) program for Sliding Stability of Concrete Structures (CSLIDE, Pace and Noddin 1987). A user interface for CSLIDE and the reliability program based on CSLIDE (called RCSLIDE) was also developed using Microsoft Visual Basic. The significance of the software development procedure described in this study is that is establishes prototype reliability software that is modular and based on an existing CASE program. Other CASE programs can be modified and utilized for reliability purposes in a similar fashion.

The development of the methodology required the definition of a performance function for retaining walls and gravity structures, development of a library of probability functions (Ayyub and Chao 1994), development of a structural reliability assessment module, development of user interfaces, and selection and performance of test cases.

Report Structure

Chapter 2 describes numerical algorithms and basic theory for the following two probability-based reliability assessment methods: (a) advanced second moment (ASM) method, and (b) Monte Carlo simulation (MCS) using direct (DR) or importance sampling (IS). Chapter 3 describes the stability analysis of concrete gravity structures and retaining walls and the CASE computer program CSLIDE. In Chapter 4, numerical algorithms for nonclosed form performance function used in the reliability analysis methods and the computer software RCSLIDE (reliability and stability assessment of concrete gravity structures) are developed. In Chapter 5, two case studies with 11 random variables are presented to illustrate the use of the developed reliability assessment software RCSLIDE. The case studies deal with noncorrelated and correlated random variables. Conclusions and recommended future work are provided in Chapters 6 and 7, respectively.

Companion Manual

The CSLIDE manual (Pace and Noddin 1987) referenced in this report is in the process of being updated to reflect the Windows version of the program and the incorporation of reliability assessment. This new report, "Reliability and Stability Assessment of Concrete Gravity Structures: User's Guide," will also be a U.S. Army Engineer Waterways Experiment Station technical report and a companion manual to this theoretical manual.

2 Structural Reliability Assessment

The reliability of an engineering system can be defined as its ability to fulfill its design purpose for some time period. The theory of probability provides the fundamental basis to measure this ability. The reliability of a structure can be viewed as the probability of its satisfactory performance according to some performance functions under specific service and extreme conditions within a stated time period. In estimating this probability, system uncertainties are modeled using random variables with mean values, variances, and probability distribution functions. Many methods have been proposed for structural reliability assessment purposes, such as first-order second moment (FOSM) method, ASM method, and computer-based MCS (e.g., Ang and Tang 1990, Ayyub and Haldar 1984, White and Ayyub 1985, Ayyub and McCuen 1997). In this chapter, two probabilistic methods for reliability assessment are described: (a) the ASM method, and (b) the MCS method using DR and IS.

Advanced Second Moment (ASM) Method

The reliability of a structure can be determined based on a performance function that can be expressed in terms of basic random variables X_i's for relevant loads and structural strength. Mathematically, the performance function Z can be described as

$$Z = Z(X_1, X_2, \ldots, X_n) = \textit{Structural strength - Load effect} \tag{1}$$

where Z is called the *performance function* of interest. The unsatisfactory performance surface (or the *limit state*) of interest can be defined as $Z = 0$. Accordingly, when $Z < 0$, the structure is in the unsatisfactory performance state, and when $Z > 0$, it is in the safe state. If the joint probability density function for the basic random variables X_i's is $f_{X_1\ X_2,\ldots,X_n}(x_1,\ _2,\ldots,x_n)$, then the unsatisfactory performance probability P_u of a structure can be given by the integral

$$P_u = \int \cdots \int f_{X_1, X_2, \ldots, X_n}(x_1, x_2, \ldots, x_n)\, dx_1\, dx_2 \ldots dx_n \tag{2}$$

where the integration is performed over the region in which $Z < 0$. In general, the joint probability density function is unknown, and the integral is a formidable task. For practical purposes, alternate methods of evaluating P_u are necessary.

Reliability index

Instead of using direct integration as given by Equation 2, the performance function Z in Equation 1 can be expanded using a Taylor series about the mean value of X's and then truncated at the linear terms. Therefore, the first-order approximate mean and variance of Z can be shown, respectively, as

$$\mu_Z \cong Z(\mu_{X_1}, \mu_{X_2}, \ldots, \mu_{X_n}) \tag{3}$$

and

$$\sigma_Z^2 = \sum_{i=1}^{n} \sum_{j=1}^{n} \left(\frac{\partial Z}{\partial X_i} \right) \left(\frac{\partial Z}{\partial X_j} \right) Cov\,(X_i, X_j) \tag{4}$$

where

μ_Z = mean of Z

μ = mean of a random variable

σ_Z^2 = variance of Z

$Cov(X_i, X_j)$ = the covariance of X_i and X_j

The partial derivatives of $\partial Z / \partial X_i$ are evaluated at the mean values of the basic random variables. For statistically independent random variables, the variance expression can be simplified as

$$\sigma_Z^2 = \sum_{i=1}^{n} \sigma_{X_i}^2 \left(\frac{\partial Z}{\partial X_j} \right)^2 \tag{5}$$

A measure of reliability can be estimated by introducing the *reliability index* β that is based on the mean and standard deviation of Z as

$$\beta = \frac{\mu_Z}{\sigma_Z} \qquad (6)$$

If Z is assumed to be normally distributed, then it can be shown that the unsatisfactory performance probability P_u is

$$P_u = 1 - \Phi(\beta) \qquad (7)$$

where Φ is the cumulative distribution function of standard normal variate.

The aforementioned procedure of Equations 3 to 7 produces accurate results when the performance function Z is normally distributed and linear.

Nonlinear performance functions

For nonlinear performance functions, the Taylor series expansion of Z is linearized at some point on the unsatisfactory performance surface called *design point*, *checking point,* or *the most likely unsatisfactory performance point* rather than at the mean. Assuming the original basic variables X_i's are uncorrelated, the following transformation can be used:

$$Y_i = \frac{X_i - \mu_{X_i}}{\sigma_{X_i}} \qquad (8)$$

If X_i's are correlated, they need to be transformed to uncorrelated random variables, as described by Thoft-Christensen and Baker (1982), Ayyub and McCuen (1997), or Ang and Tang (1990) and described in the later section entitled "Correlated random variables." The reliability index β is defined as the shortest distance to the unsatisfactory performance surface from the origin in the reduced Y-coordinate system. The point on the unsatisfactory performance surface that corresponds to the shortest distance is the most likely unsatisfactory performance point. Using the original X-coordinate system, the reliability index β and design point $(X_1^*, X_2^*, \ldots, X_n^*)$ can be determined by solving the following system of nonlinear equations iteratively for β:

$$\alpha_i = \frac{\left(\frac{\partial Z}{\partial X_i}\right)\sigma_{X_i}}{\left[\sum_{i=1}^{n}\left(\frac{\partial Z}{\partial X_i}\right)^2 \sigma_{X_i}^2\right]^{1/2}} \qquad (9)$$

$$X_i^* = \mu_{X_i} - \alpha_i \beta \sigma_{X_i} \tag{10}$$

$$Z(X_1^*, X_2^*, \ldots, X_n^*) = 0 \tag{11}$$

where α_i is a directional cosine and the partial directives are evaluated at the design point, indicated by an asterisk. Then, Equation 7 can be used to evaluate P_u. However, this formulation is limited to normally distributed random variables. In reliability assessment, the directional cosines can be viewed as measures of the importance of the corresponding random variables in determining the reliability index β. Also, partial safety factors γ that are used in load and resistance factor design (LRFD) can be computed as follows:

$$\gamma = \frac{X^*}{\mu_X} \tag{12}$$

In general, partial safety factors take on values larger than one for load variables (called in this case load amplification factors), and values less than one for strength variables (called in this case strength reduction factors).

Equivalent normal distributions

If a random variable X is not normally distributed, then it needs to be transformed to an equivalent normally distributed random variable, indicated by the superscript N. The parameters of the equivalent normal distribution, $\mu_{X_i}^N$ and σ_X^N, can be estimated by imposing two conditions (Rackwitz and Fiessler 1976, 1978). The cumulative distribution functions (CDF) and probability density functions of a nonnormal random variable and its equivalent normal variable should be equal at the design point on the unsatisfactory performance surface. The first condition can be expressed as

$$\Phi\left(\frac{X_i^* - \mu_{X_i}^N}{\sigma_{X_i}^N}\right) = F_i(X_i^*) \tag{13}$$

The second condition is

$$\phi\left(\frac{X_i^* - \mu_{X_i}^N}{\sigma_{X_i}^N}\right) = f_i(X_i^*) \tag{14}$$

where

F_i = nonnormal cumulative distribution function

ϕ = probability density function of standard normal variate

f_i = nonnormal probability density function

The standard deviation and mean of equivalent normal distributions can be shown, respectively, to be

$$\sigma_{X_i}^N = \frac{\phi\{\Phi^{-1}[F_i(X_i^*)]\}}{f_i(X_i^*)} \tag{15}$$

and

$$\mu_{X_i}^N = X_i^* - \Phi^{-1}[F_i(X_i^*)]\sigma_{X_i}^N \tag{16}$$

Having determined $\sigma_{X_i}^N$ and $\mu_{X_i}^N$ for each random variable, β can be solved using the same procedure of Equations 9-11.

The ASM method is capable of dealing with nonlinear performance functions and nonnormal probability distributions. However, the accuracy of the solution and the convergence of the procedure depend on the nonlinearity of the performance function in the vicinity of design point and the origin. If there are several local minimum distances to the origin, the solution process may not converge onto the global minimum. The probability of unsatisfactory performance is calculated from the reliability index β using Equation 7, which is based on normally distributed performance functions. Therefore, the resulting unsatisfactory performance probability P_u based on the ASM is approximate except for linear performance functions because it does not account for any nonlinearity in the performance functions.

Correlated random variables

Reliability analysis of gravity structures needs to be based on correlated soil properties such as angle of internal friction and cohesion for soil layers. In this section, this correlation is assumed to occur between pairs of random variables for each layer. Also, correlated random variables are assumed to be normally distributed since nonnormal and correlated random variables require additional information such as their joint probability density function or conditional distributions for their unique and full definition (Ang and Tang 1990). Such information is commonly not available and difficult to obtain. A correlated (and normal) pair of random variables X_1 and X_2 with a correlation coefficient ρ can be transformed into noncorrelated pair Y_1 and Y_2 by solving for two eigenvalues λ and the corresponding eigenvectors as follows:

$$Y_1 = \frac{1}{2t}\left(\frac{X_1 - \mu_{X_1}}{\sigma_{X_1}} + \frac{X_2 - \mu_{X_2}}{\sigma_{X_2}}\right) \tag{17}$$

$$Y_2 = \frac{1}{2t}\left(\frac{X_1 - \mu_{X_1}}{\sigma_{X_1}} - \frac{X_2 - \mu_{X_2}}{\sigma_{X_2}}\right) \tag{18}$$

where $t = \sqrt{0.5}$. The resulting Y variables are noncorrelated with respective variances that are equal to the eigenvalues λ as follows:

$$\sigma_{Y_1}^2 = \lambda_1 = 1 + \rho \tag{19}$$

$$\sigma_{Y_2}^2 = \lambda_2 = 1 - \rho \tag{20}$$

For a correlated pair of random variables, Equations 9 and 10 need to be revised respectively to the following:

$$\alpha_{Y_1} = \frac{\left[\left(\frac{\partial Z}{\partial X_1}\right)t\sigma_{X_1} + \left(\frac{\partial Z}{\partial X_2}\right)t\sigma_{X_2}\right]\sqrt{1+\rho}}{\left[\left(\frac{\partial Z}{\partial X_1}\right)^2\sigma_{X_1}^2 + \left(\frac{\partial Z}{\partial X_2}\right)^2\sigma_{X_2}^2 + 2\rho\left(\frac{\partial Z}{\partial X_1}\right)\left(\frac{\partial Z}{\partial X_2}\right)\sigma_{X_1}\sigma_{X_2}\right]^{1/2}} \tag{21}$$

$$\alpha_{Y_2} = \frac{\left[\left(\frac{\partial Z}{\partial X_1}\right)t\sigma_{X_1} - \left(\frac{\partial Z}{\partial X_2}\right)t\sigma_{X_2}\right]\sqrt{1-\rho}}{\left[\left(\frac{\partial Z}{\partial X_1}\right)^2\sigma_{X_1}^2 + \left(\frac{\partial Z}{\partial X_2}\right)^2\sigma_{X_2}^2 + 2\rho\left(\frac{\partial Z}{\partial X_1}\right)\left(\frac{\partial Z}{\partial X_2}\right)\sigma_{X_1}\sigma_{X_2}\right]^{1/2}} \tag{22}$$

and

$$X_1^* = \mu_{X_1} - \sigma_{X_1} t\beta\left(\alpha_{Y_1}\sqrt{\lambda_1} + \alpha_{Y_2}\sqrt{\lambda_2}\right) \tag{23}$$

$$X_2^* = \mu_{X_2} - \sigma_{X_2} t\beta\left(\alpha_{Y_1}\sqrt{\lambda_1} - \alpha_{Y_2}\sqrt{\lambda_2}\right) \tag{24}$$

where the partial derivatives are evaluated at the design point.

Numerical algorithms

The ASM method can be used to assess the reliability of a structure according to a nonlinear performance function that may include nonnormal random variables. Also, the performance function can be in a closed or nonclosed form expression. The implementation of this method requires the use of efficient and accurate numerical algorithms in order to deal with the nonclosed forms for performance function. The ASM algorithm can be summarized by the following steps using two cases:

Algorithm 2-1 (noncorrelated random variables). Use the following steps:

(1) Assign the mean value for each random variable as a starting design point value, i.e., $(X_1^*, X_2^*, \ldots, X_n^*) = (\mu_{X_1}, \mu_{X_2}, \ldots, \mu_{X_n})$.

(2) Compute the standard deviation and mean of the equivalent normal distribution for each nonnormal random variable using Equations 13-16.

(3) Compute the partial derivative $\partial Z/\partial X_i$ of the performance function with respect to each random variable evaluated at the design point as needed by Equation 9.

(4) Compute the directional cosine α_i for each random variable as given in Equation 9 at the design point.

(5) Compute the reliability index β by substituting Equation 10 into Equation 11 and satisfying the limit state $Z = 0$ in Equation 11 using a numerical root-finding method.

(6) Compute a new estimate of the design point by substituting the resulting reliability index β obtained in Step 5 into Equation 10.

(7) Repeat Steps 2 to 6 until the reliability index β converges within an acceptable tolerance δ.

End of Algorithm 2-1.

Algorithm 2-2 (correlated random variables). Use the following steps:

(1) Assign the mean value for each random variable as a starting design point value, i.e., $(X_1^*, X_2^*, \ldots, X_n^*) = (\mu_{X_1}, \mu_{X_2}, \ldots, \mu_{X_n})$.

(2) Compute the standard deviation and mean of the equivalent normal distribution for each nonnormal random variable using Equations 13-16.

(3) Compute the partial derivative $\partial Z/\partial X_i$ of the performance function with respect to each noncorrelated random variable evaluated at the design point as needed by Equation 9.

(4) Compute the directional cosine α_i for each noncorrelated random variable as given in Equation 9 at the design point. For correlated pairs of random variables, Equations 21 and 22 should be used.

(5) Compute the reliability index β by substituting Equations 10 (for noncorrelated random variables) and 23 and 24 (for correlated random variables) into Equation 11 and satisfying the limit state $Z = 0$ in Equation 11 using a numerical root-finding method.

(6) Compute a new estimate of the design point by substituting the resulting reliability index β obtained in Step 5 into Equations 10 (for noncorrelated random variables) and 23 and 24 (for correlated random variables).

(7) Repeat Steps 2 to 6 until the reliability index β converges within an acceptable tolerance δ.

End of Algorithm 2-2.

Monte Carlo Simulation (MCS) Methods

Monte Carlo simulation techniques are basically sampling processes that are used to estimate the unsatisfactory performance probability of a structure. The basic random variables in Equation 1 are randomly generated (Press et al. 1992; Ayyub and McCuen 1997; Ayyub and Chao 1994) and substituted into Equation 1. Then the fraction of cases that resulted in unsatisfactory performance are determined in order to assess unsatisfactory performance probability. Two methods are described in this section: the direct MCS and the IS.

Direct MCS method

The direct simulation method comprises drawing samples of the basic noncorrelated variables according to their corresponding probabilistic characteristics and then feeding them into the performance function Z as given by Equation 1. Assuming N_u to be the number of simulation cycles for which $Z < 0$ in a total N simulation cycles, then an estimate of the mean unsatisfactory performance probability can be expressed as

$$\overline{P}_u = \frac{N_u}{N} \tag{25}$$

The estimated unsatisfactory performance probability $\overline{P}_u$ should approach the true value for the population when N approaches infinity. The variance of the estimated unsatisfactory performance probability can be approximately computed using the variance expression for a binomial distribution as

$$Var(\overline{P}_u) = \frac{(1-\overline{P}_u)\overline{P}_u}{N} \tag{26}$$

Therefore, the coefficient of variation (*COV*) of the estimated unsatisfactory performance probability is

$$COV(\overline{P}_u) = \frac{1}{\overline{P}_u}\sqrt{\frac{(1-\overline{P}_u)\overline{P}_u}{N}} \tag{27}$$

These equations show that direct simulation can be economically prohibitive in some cases, especially for small unsatisfactory performance probabilities. In the subsequent section, the IS method is described for the purpose of increasing the efficiency of simulation.

Importance sampling

The probability of unsatisfactory performance of a structure according to the performance function of Equation 1 is provided by the integral of Equation 2. In the evaluation of this integral with direct simulation, the efficiency of the simulation process depends on the magnitude of the probability of unsatisfactory performance, i.e., the location of the most likely unsatisfactory performance point or design point as defined in the section "Nonlinear performance functions." The larger the margin of safety (Z) and the smaller its variance, the larger the simulation effort needed to obtain sufficient simulation runs with unsatisfactory performances; in other words, smaller unsatisfactory performance probabilities require larger numbers of simulation cycles. This deficiency can be addressed by using importance sampling. In this method, the basic random variables are generated according to some carefully selected probability distributions (called importance density function, $h_{\underline{X}}(\underline{x})$) with mean values that are closer to the design point than their original (actual) probability distributions. It should be noted that the design point is not known in advance; the analyst can only guess. Therefore, simulation runs with unsatisfactory performances are obtained more frequently and the simulation efficiency is increased. To compensate for the change in the probability distributions, the results of the simulation cycles should be corrected. The fundamental equation for this method is given by

$$\overline{P}_u = \frac{1}{N}\sum_{i=1}^{N} I_i \frac{f_{\underline{X}}(x_{1i}, x_{2i}, \ldots, x_{ni})}{h_{\underline{X}}(x_{1i}, x_{2i}, \ldots, x_{ni})} \tag{28}$$

where

I = performance indicator function that takes values of either 0 for unsatisfactory performance or 1 for survival

$f_{\underline{X}}(x_{1i}, x_{2i}, \ldots, x_{ni})$ = the original joint density function of the basic random variables evaluated at the i^{th} generated values of the basic random variables

$h_{\underline{X}}(x_{1i}, x_{2i}, \ldots, x_{ni})$ = the selected joint density function of the basic random variables evaluated at the i^{th} generated values of the basic random variables

For noncorrelated basic random variables, the joint density function $f_{\underline{X}}(x_{1i}, x_{2i}, \ldots, x_{ni})$ can be replaced by the product of the density functions of the individual random variables. Similarly, the joint $h_{\underline{X}}(x_{1i}, x_{2i}, \ldots, x_{ni})$ can be replaced by the product of the corresponding importance density functions. In Equation 28, $h_{\underline{X}}(\underline{x})$ is called the sampling (or weighting) density function or the importance function. Efficiency (and thus the required number of simulation cycles) depends on the choice of this sampling density function. The coefficient of variation of the estimated unsatisfactory performance probability can be based on the variance of a sample mean as follows:

$$COV(\overline{P}_u) = \frac{\sqrt{\frac{1}{N(N-1)} \sum_{i=1}^{N} \left[I_i \frac{f_{\underline{X}}(x_{1i}, x_{2i}, \ldots, x_{ni})}{h_{\underline{X}}(x_{1i}, x_{2i}, \ldots, x_{ni})} - \overline{P}_u \right]^2}}{\overline{P}_u} \qquad (29)$$

Additional information on importance sampling can be found in Schueller and Stix (1987).

Correlated random variables

In this section, correlation between pairs of random variables is treated for simulation purposes. Similar to the previous section in this chapter on correlated random variables for ASM, correlated random variables are assumed to be normally distributed since nonnormal and correlated random variables require additional information such as marginal probability distribution for their unique and full definition. Such information is commonly not available and difficult to obtain. A correlated (and normal) pair of random variables X_1 and X_2 with a correlation coefficient ρ can transformed using linear regression transformation as follows:

$$X_2 = b_0 + b_1 X_1 + \varepsilon \qquad (30)$$

where

b_0 = the intercept of a regression line between X_1 and X_2

b_1 = slope of the regression line

ε = random (standard) error with a mean of zero and a standard deviation as given in Equation 33

These regression model parameters can be determined in terms of the probabilistic characteristics of X_1 and X_2 as follows:

$$b_1 = \frac{\rho \sigma_{X_2}}{\sigma_{X_1}} \tag{31}$$

$$b_0 = \mu_{X_2} - b_1 \mu_{X_1} \tag{32}$$

$$\sigma_\varepsilon = \sigma_{X_2} \sqrt{1 - \rho^2} \tag{33}$$

The simulation procedure for a correlated pair of random variables (X_1 and X_2) can then be summarized as follows:

a. *Step 1:* Compute the intercept of a regression line between X_1 and X_2 (b_0), the slope of the regression line (b_1), and the standard deviation of the random (standard) error (ε) using Equations 31-33.

b. *Step 2:* Generate a random (standard) error using a zero mean and a standard deviation as given by Equation 33.

c. *Step 3:* Generate a random value for X_1 using its probabilistic characteristics (mean and variance).

d. *Step 4:* Compute the corresponding value of X_2 as follows (based on Equation 30):

$$x_2 = b_0 + b_1 x_1 + \varepsilon \tag{34}$$

where b_0 and b_1 are computed in Step 1; ε is a generated random (standard) error from Step 2; and x_1 is a generated value from Step 3.

e. *Step 5:* Use the resulting random (but correlated) values of x_1 and x_2 in the simulation-based reliability assessment methods.

This procedure is applicable for both the DR method and IS. In the case of IS, correlated random variables should not be selected for defining the sampling (or importance) density function ($h_{\underline{X}}$).

3 Stability Analysis of Concrete Gravity Structures

The reliability assessment of the sliding stability of gravity concrete structures requires the definition of strength, loads, and reliability methods. In this chapter, the sliding stability strength and loads needed for reliability assessment are briefly described. The strength and loads models were based on the models that are used in the sliding stability for concrete structures (CSLIDE) program (Pace and Noddin 1987).

The first section of this chapter provides theoretical background information on computing the strength and load for the sliding stability for a concrete gravity structure. The only failure mode that is handled in this study is the sliding stability mode. In the second section, the CSLIDE computer program is briefly described and referenced.

Theoretical Basis

Gravity concrete structures serve a vital function in many Corps facilities such as navigation locks and dams. A gravity structure supports earth and water pressures on both its sides and bottom. The purpose of sliding stability analysis is to assess the ability of the structure in fulfilling its function without an excessive horizontal deformation. An excessive horizontal deformation can be viewed as a unsatisfactory performance of the structure. In order to make such an assessment, the sliding strength or resistance in the form of its maximum shear strength R and the applied load L in the form of an applied shear need to be evaluated. A safety factor SF or margin of safety can then be estimated as

$$SF = \frac{R}{L} \tag{35}$$

As this ratio (SF) becomes 1 or smaller, the potential of unsatisfactory performance in terms of sliding stability of a structure becomes more imminent.

The unsatisfactory performance in sliding stability for a structure occurs along a theoretical failure surface, which is identified only for analysis purposes and does not necessarily reflect a catastrophic failure of the structure. The failure surface may be irregular depending on the homogeneity of the backfill and the foundation materials. Therefore, the failure surface can be a combination of failure planes and curved surfaces. The stability analysis can accordingly be reduced to static evaluation of assumed wedges of failed materials with assumed force directions at the interaction surfaces between the edges. Therefore, a wedge configuration is determined that meets the conditions of statics. Once the wedge configuration is determined, the R and L terms in Equation 35 are determined using statics. Then, the safety factor is evaluated.

The analysis in CSLIDE is based on a set of assumptions (Pace and Noddin 1987) that includes (a) wedge interfaces as vertical planes, (b) a kinematically possible failure surface that consists of linear segments, (c) two-dimensional static analysis of edges, (d) the shear resistance that is determined using Mohr-Coulomb failure criteria, (e) force equilibrium that is satisfied, (f) moment equilibrium not considered, (g) negligible shear forces at wedge interfaces, (h) wedges that have the same safety factor, (i) small displacements that do not have any effect on resulting wedge forces, and (j) the structure that produces one structure wedge because of its relatively high shear strength. Usually, an iterative computational procedure is needed to determine the SF that produces force equilibrium for the edges. The iterative procedures are described by Pace and Noddin (1987).

CSLIDE Program

The sliding stability of concrete structures (CSLIDE) program (Pace and Noddin 1987) is based on the theory discussed in the preceding section. The program was written in FORTRAN and was revised to run in a batch mode using an input file. An output file of CSLIDE includes the safety factor as defined in Equation 35. The program performs deterministic evaluation of SF based on its input.

An input file of CSLIDE consists of the following information: (a) structural edge; (b) soil on both sides of a structure; (c) soil below the structure, (d) methods of analysis that include single plane, multi-plane, and variable angles; (e) water information; (f) input wedge angles; and (g) loads. Therefore, CSLIDE can handle a variety of soil geometries, structural geometries, and loading conditions.

CSLIDE has the following limitations: (a) the number of wedges must equal the number of soil layers; (b) soil profiles cannot intersect; (c) once the base of a wedge is determined in a soil layer, the remaining soil profile beyond the base of the wedge is ignored; and (d) failure occurs from left to right.

4 Reliability Assessment for Concrete Gravity Structures

The reliability of sliding stability for concrete retaining walls and gravity structures can be assessed using the reliability methods described in Chapter 2. In the first section of this chapter, a reliability assessment model based on the ASM method is introduced. Numerical algorithms for computing derivatives and finding roots of equations are also described. In the second section, a model for using DR MCS and IS is described. In the last section, the development of the reliability assessment software (RCSLIDE) is also described.

Performance Function

The SF for the sliding stability of concrete retaining walls and gravity structures can be obtained by using CSLIDE (Pace and Noddin 1987) and can be expressed as

$$SF = \frac{R}{L} \tag{36}$$

where

R = resistance in the form of a restoring strength

L = load effect in the form of the sliding force

From Equation 36, the resistance $R = (SF)L$. Therefore, the performance function Z of Equation 1 is given by

$$Z = R - L = (SF)L - L = L(SF - 1) \tag{37}$$

Dividing both side by L produces the following revised performance function G

$$G = \frac{Z}{L} = SF - 1 \tag{38}$$

Therefore, by utilizing CSLIDE to obtain *SF*, Equation 38 becomes a nonclosed expression of the performance function as follows:

$$G = SF(X_1, X_2, \cdots, X_n) - 1 \tag{39}$$

where X_i = a basic strength random variable such as geometry, material property, and loads that are input quantities to CSLIDE as described in Chapter 3.

Advanced Second Moment (ASM) Method

The ASM method as described in Chapter 2 requires a closed-form expression of a performance function (Equation 1). In Equation 39, *SF* is not in a closed-form expression. The objective of this section is to introduce the needed changes to the ASM method in order to handle nonclosed forms of the performance function.

The first change to the method is needed in computing the directional cosines as given in Equations 9, 21, and 22 for each random variable. These directional cosines require the computation of the partial derivatives of G with respect to the random variables. The partial derivatives with respect to X_i can be determined as

$$\frac{\partial G}{\partial X_i} = \frac{\partial G}{\partial SF}\frac{\partial SF}{\partial X_i} = (1)\frac{\partial SF}{\partial X_i} = \frac{\partial SF}{\partial X_i} = \frac{\partial SF(X_1, X_2, \cdots X_n)}{\partial X_i} \tag{40}$$

The partial derivative with respect to each X_i in Equation 40 cannot be determined analytically. Therefore, a numerical method for computing these partial derivatives is needed and is described later in this chapter as Algorithm 4-1. The directional cosine for each random variable can now be determined as given by Equations 9, 21, and 22.

The second change to the method is needed in solving for the reliability index β by substituting Equations 10, 23, and 24 into Equation 39. This solution requires finding the root for the following expression:

$$G = SF(X_1, X_2, \cdots, X_n) - 1 = G(\beta) = 0 \tag{41}$$

where $G(\beta) = G$ as a function of β. Therefore, a numerical method for finding the roots of nonlinear equations is needed and is described later in this chapter as Algorithms 4-2 and 4-3. After β is found, the design point is updated according to Equations 10, 23, and 24, and this completes Steps 5 and 6 in Algorithms 2-1 and 2-2.

Numerical differentiation

By definition, if a function $f(x)$ is continuous in the domain of x, then the derivative of $f(x)$ can be expressed as follows:

$$\frac{df(x)}{dx} = \lim_{\Delta x \to 0} \frac{f(x+\Delta x) - f(x)}{\Delta x} \tag{42}$$

The accuracy of computing the derivative in Equation 42 can be improved as follows:

$$\frac{df(x)}{dx} = \lim_{\Delta x \to 0} \frac{f(x+\Delta x) - f(x-\Delta x)}{2\Delta x} \tag{43}$$

Therefore, the partial derivative for each X_i in Equation 40 can be expressed as

$$\frac{\partial SF}{\partial X_i} = \lim_{\Delta X \to 0} \frac{SF(X_1, X_2, \cdots, X_i + \Delta X, \cdots, X_n) - SF(X_1, X_2, \cdots, X_i - \Delta X, \cdots, X_n)}{2\Delta X_i} \tag{44}$$

Because this numerical approach can be applied to both closed and nonclosed expressions, it meets the purposes of computer usage for reliability assessment.

Algorithm 4-1. Based on Equation 9, the numerical algorithm for computing the partial derivative for a random variable X_i in *SF* can be summarized as follows:

a. Step 1: Compute $X_i + \Delta X_i$, in which ΔX_i is a specified very small quantity (or increment).

b. *Step 2*: Compute $SF_1 = SF(X_1, X_2, \cdots, X_i + \Delta X_i, \cdots, X_n)$ using CSLIDE.

c. *Step 3*: Compute $X_i - \Delta X_i$, in which ΔX_i is a specified very small quantity (or increment).

d. *Step 4*: Compute $SF_2 = SF(X_1, X_2, \cdots, X_i - \Delta X_i, \cdots, X_n)$ using CSLIDE.

e. *Step 5*: Estimate $\partial SF / \partial X_i \approx (SF_1 - SF_2) / 2\Delta X_i$.

f. *Step 6*: Repeat Steps 1 to 5 for each X_i .

End of Algorithm 4-1.

Numerical solution for roots of equations

Newton's method for root finding is commonly used for this purpose, but this method does not always converge to the true values for some cases (Ayyub and McCuen 1996). Besides, Newton's method requires the evaluation of derivative. The bisection method always converges, but the speed of finding roots within an acceptable tolerance for a nonlinear equation can be slow. Therefore, a root-finding method called linear interpolation method or regula falsi method (Gerald and Wheatley 1984) is adopted herein. This method always converges, and its convergence rate is somewhat slower than Newton's method and faster than the bisection method.

Assuming that a function $f(x)$ is continuous in $[a, b]$, and $f(a)$ and $f(b)$ are of opposite signs, the algorithm for the regula falsi method can be stated as follows (Gerald and Wheatley 1984):

Algorithm 4-2.

```
Do While (|b-a|≥tolerance_1 or |f(c)|≥tolerance_2)
      c=b-f(b)*(b-a)/(f(b)-f(a))
      If f(c)*f(a)<0 Then
            b=c
      Else
            a=c
      End If
End Do
```

End of Algorithm 4-2.

In cases where $f(x)$ has a significant curvature between *a* and *b*, the convergence speed becomes slow (Gerald and Wheatley 1984). To improve convergence speed in this case, a modified linear interpolation method can be used. According to the modified method, the value of $f(x)$ at the unchanged end position is replaced with $f(x)/2$ as described in the following revised algorithm (Gerald and Wheatley 1984):

Algorithm 4-3.

```
Fa=f(a); Fb=f(b); FF=f(a)
Do While (|b-a|≥tolerance_1 or |Fc|≥tolerance_2)
      c=b-Fb*(b-a)/(Fb-Fa)
      Fc=f(c)
      If Fc*Fa < 0 Then
             b=c
             Fb=Fc
             If Fc*FF>0 Then Fa=Fa/2
      Else
             a=c
             Fa=Fc
             If Fc*FF > 0 Then Fb=Fb/2
      End If
```

```
      FF=Fc
End Do
```

End of Algorithm 4-3.

The implementation of computer programs in ASM for finding β was based on the modified linear interpolation method. After β is found, the design point is updated according to Equations 10, 23, and 24, and this completes Steps 5 and 6 in Algorithms 2-1 and 2-2.

Flowchart

The procedure for reliability assessment of concrete retaining walls and gravity structures using the ASM method according to Algorithms 2-1, 2-2, 4-1, and 4-3 is shown in Figure 1 in the form of a flowchart. The computer program developed based on this flowchart results in the reliability index β, unsatisfactory performance probability P_u, directional cosine α_i, partial safety factors for the input random variables, and the design point.

Monte Carlo Simulation (MCS) Methods

The performance function in Equation 40 can also be used in MCS methods for reliability assessment of concrete retaining walls and gravity structures. For the purpose of IS, Equation 40 does not indicate which random variables are on the resistance side (R) and which random variables are on the load-effect side (L). Therefore, a sensitivity test for each random variable is needed to allocate each random variable to either a resistance or loading side. Some random variables might not belong to the L side nor to the R side; therefore, they can be assigned to a neutral side for use in the importance sampling procedure.

Algorithm 4-4. The sensitivity test can be performed using the following proposed algorithm:

a. Step 1: Compute $SF = SF(X_1, X_2, \cdots, X_i, \cdots, X_n)$ using CSLIDE.

b. Step 2: Compute $X_i + \Delta X_i$, in which ΔX_i is a specified very small quantity (or increment).

c. Step 3: Compute $SF_1 = SF(X_1, X_2, \cdots, X_i + \Delta X_i, \cdots, X_n)$ using CSLIDE.

d. Step 4: $DIFF_1 = SF_1 - SF$.

e. Step 5: Compute $X_i - \Delta X_i$, in which ΔX_i is a specified very small quantity (or increment).

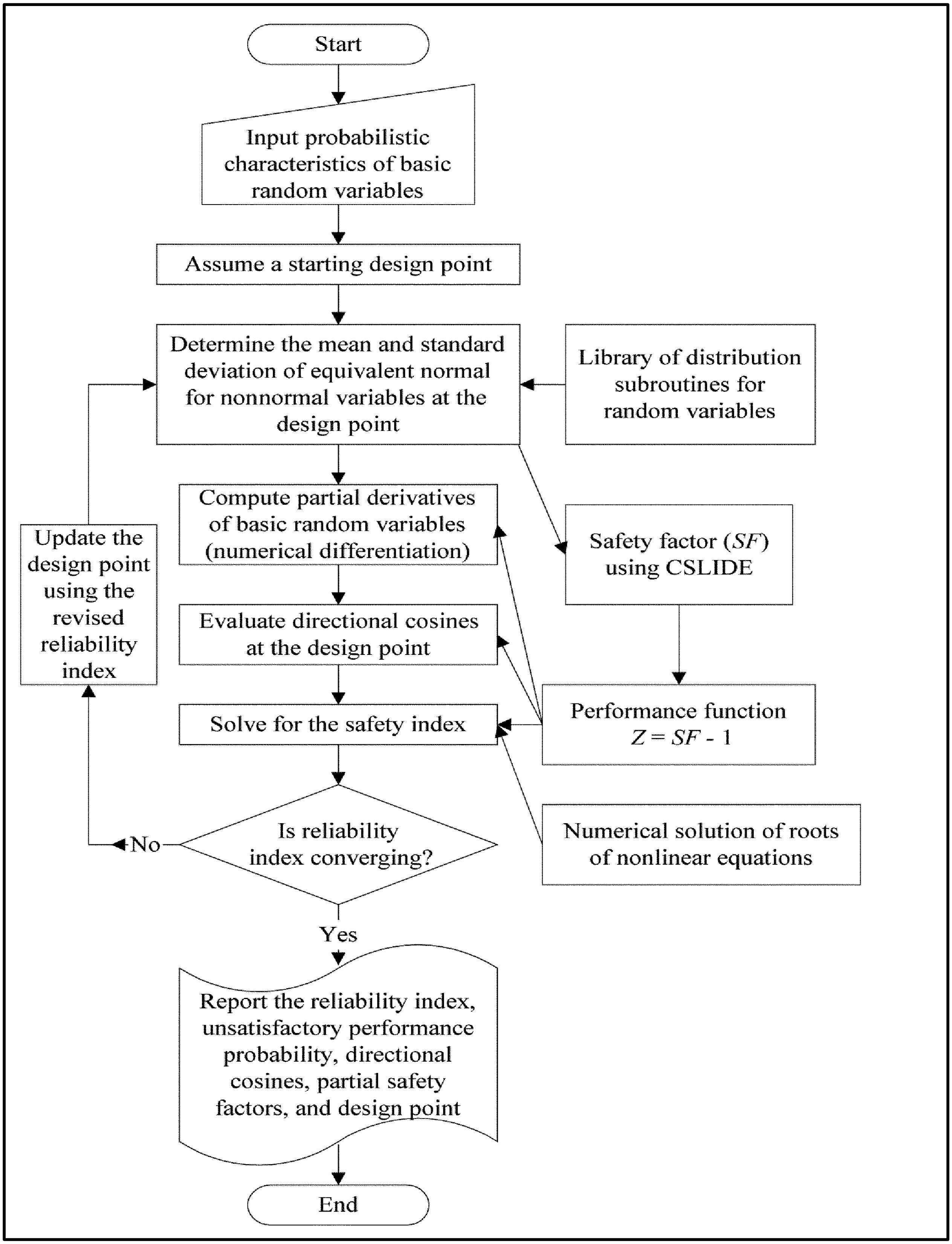

Figure 1. Advanced second moment method flowchart

f. *Step 6*: Compute $SF_2 = SF(X_1, X_2, \cdots, X_i - \Delta X_i, \cdots, X_n)$ using CSLIDE.

g. *Step 7*: $DIFF_2 = SF_2 - SF$

h. *Step 8*: If $DIFF_1 = DIFF_2$, Then X_i is on neutral side, Else If $DIFF_1 < DIFF_2$ Then X_i is on loading side, Else X_i is on resistant side.

i. *Step 9*: Repeat Steps 2 to 8 for each X_i .

End of Algorithm 4-4.

After the sensitivity tests are completed for all the random variables, the shifting direction of the mean value of each random variable can be determined for the importance sampling method. A random number generator (Press et al. 1992) is then used to produce random numbers as CDF values for the corresponding basic random variables. The inverse transformation method (Law and Kelton 1991) according to the shifted mean values and unchanged standard deviations is used to obtain the corresponding generated values for the basic variables.

Estimates of the probability of unsatisfactory performance P_u and its coefficient of variation can be computed using Equations 28 and 29, respectively.

The IS method requires that the distributions of some of the basic random variables be shifted according to Algorithm 4-4 in order to increase the chance of obtaining unsatisfactory performance in the simulation runs. As a measure of the significance of shifting these variables on the performance of the IS method, a shifted safety factor SF_s based on a CSLIDE run using the shifted mean values of the basic random variables can be utilized. The random variables can be shifted using different levels that depend on their estimated effects on *SF* based on the sensitivity analysis of Algorithm 4-4. The random variables need to be incrementally shifted until some target level for the safety factor SF_t is achieved that can ensure the desired IS performance. In the case of correlated random variables, these variables should not be selected for defining the sampling (or importance) density function $h_{\underline{X}}$. The target safety factor should be smaller than the first-order mean safety factor SF_m based on the mean values of the unshifted random variables. The smallest value the target safety factor can take is one, which corresponds to a point on the unsatisfactory performance surface. A user of this method needs to specify a target safety factor based on judgment. The larger the target *SF* value, the smaller the efficiency of the IS method. On the other hand, the smaller the target *SF* value, the larger the shift of the probability distributions of the shifted basic random variables, which might result in violating some limits or constraints that are internal to the CSLIDE program. A large shift in some random variables can result in warning messages by CSLIDE due to violating some internal limits and constraints within CSLIDE; e.g., water levels on the two sides of the structure are below the structure and are not at the same elevation. Therefore, the safety factor target should be selected carefully; the larger the target safety factor, the better IS performance with a penalty of an increased number of simulation cycles needed. Using the design point as a shifting mean for the target safety factor is not necessarily a good choice for IS with a nonclosed performance function.

The procedure for reliability assessment of concrete retaining walls and gravity structures using importance sampling and direct MCS is shown in Figure 2 in the form of a flowchart. The computer program developed based on this flowchart results in the estimated unsatisfactory performance probability.

Development of RCSLIDE Software

The software RCSLIDE (reliability and stability assessment of concrete structures) provides stability analysis and reliability assessment of concrete retaining walls and gravity structures with a user-friendly interface. RCSLIDE contains the following three main analysis functions: (a) stability analysis for concrete retaining walls and gravity structures using CSLIDE, (b) reliability assessment using ASM method, and (c) reliability assessment using MCS with IS and DR. In addition to these three main analysis functions, the user interface of the software for RCSLIDE allows the preparation of input data for running these three main analysis functions, viewing the results of the analysis, and plotting the simulation results and structural geometry. The analysis functions were all written in FORTRAN, and the interface portion was written in Microsoft Visual BASIC.

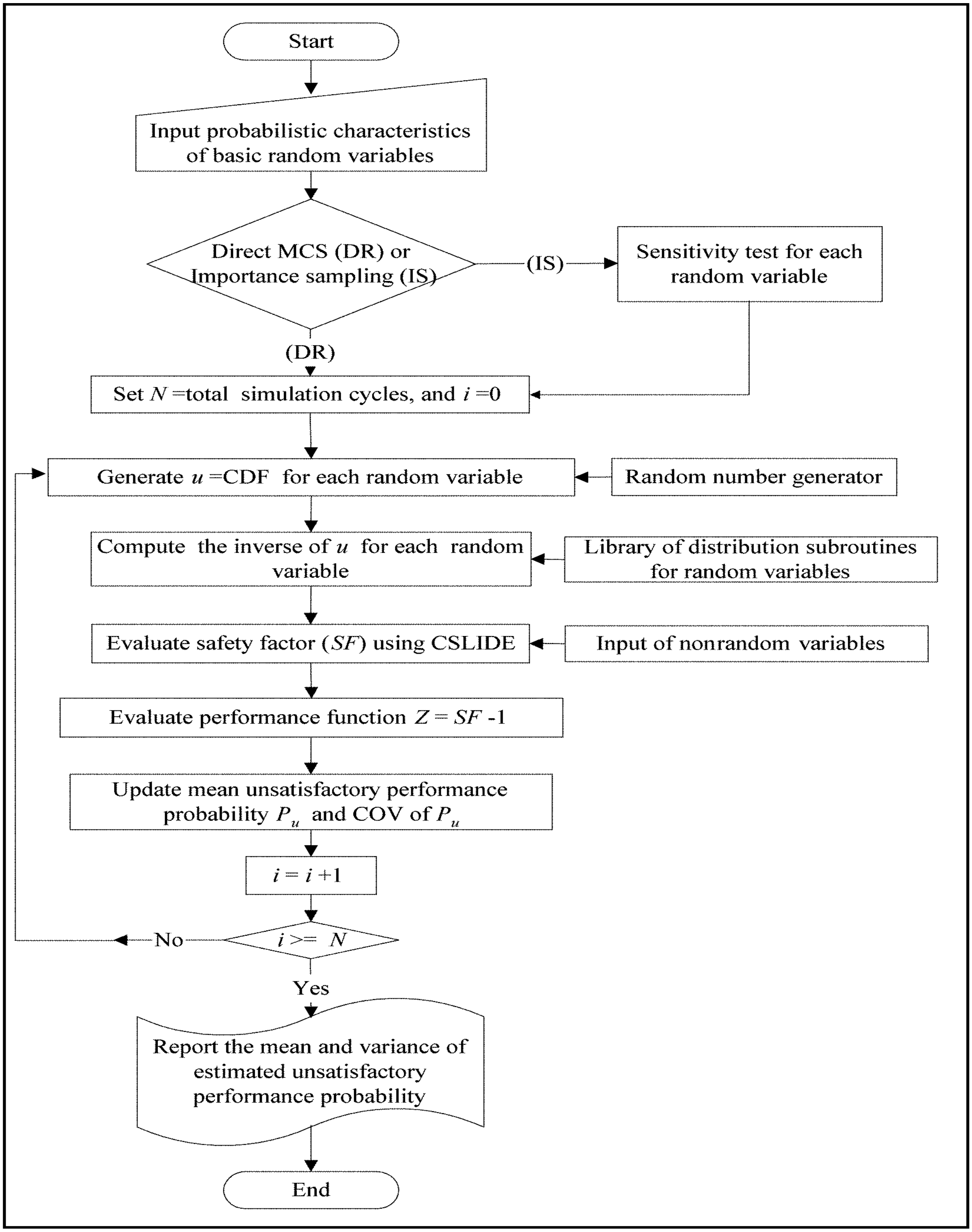

Figure 2. Monte Carlo simulation flowchart

5 Case Studies

Two case studies were developed in this study for noncorrelated and correlated random variables. The primary objective of these case studies was to examine the computational accuracy of the reliability methods. Probabilistic characteristics of random variables and/or reliability results are not necessarily representative of real gravity structures.

Noncorrelated Random Variables

An example with 11 random variables is described in this section to illustrate reliability assessment of the sliding stability of gravity concrete structures using the developed software RCSLIDE. The ASM method, MCS, and IS are used in this example.

A typical gravity concrete structure (Figure 3) was selected from the example cases in the user's manual for CSLIDE (Pace and Noddin 1987). The selected structure involves soil and water pressure on both its sides and vertical surcharges. Eleven random variables were then identified and selected from the input to CSLIDE. The random variables were chosen from structural, soil, and loading properties. These variables and their statistical characteristics were selected for the purpose of demonstration, and they do not necessarily reflect real variables or real statistics. The 11 random variables are shown in Table 1. Table 2 shows the final unsatisfactory performance probability assessment results based on the ASM method. Figures 4-6 show the unsatisfactory performance probability assessment results based on simulation methods with different SF_t values and different seed values. The results for both ASM and MCS are summarized in Table 3. The detailed input data and results for CSLIDE and RCSLIDE are provided in Appendix A.

Table 3 and Figures 4-6 show that the results using ASM, IS, and direct MCS are quite in agreement except for the results based on importance sampling with an SF_t of 1.0. The disagreement in this case can be attributed to the large shift of random variables according to the importance function that resulted in an SF_t of 1.0. The large shift in this case resulted in warning messages by CSLIDE due to violating some internal limits and constraints within CSLIDE; e.g., water levels on

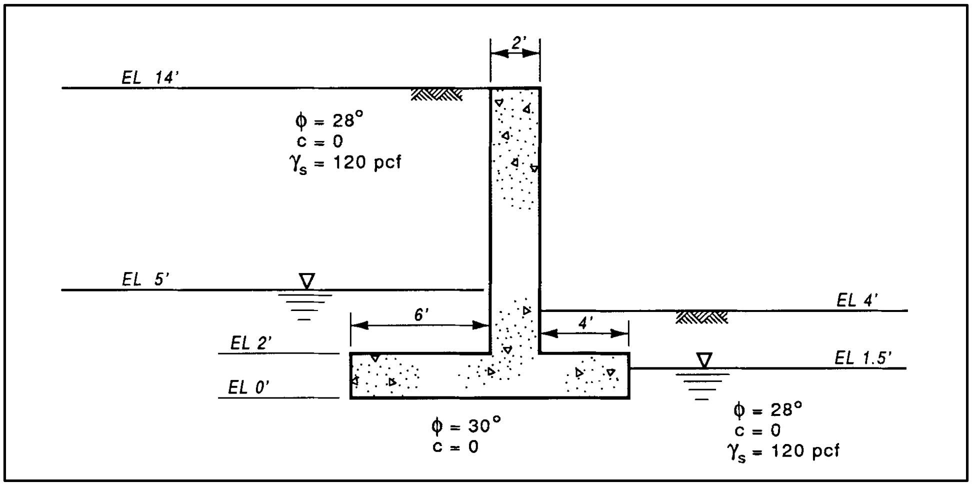

Figure 3. Retaining wall

Table 1
Characteristics of Input Random Variables

X (1)	Name (2)	Meaning (3)	Mean (4)	COV(Stddv) (5)	Type (6)
1	GAMC	Equivalent structure unit weight, kcf	0.15	0.15	Normal
2	PHIL	Angle of internal friction, deg (left-side soil)	28.00	0.30	Normal
3	GAML	Layer moist unit weight, kcf (left-side soil)	0.12	0.10	Normal
4	PHIR	Angle of internal friction, deg (right-side)	28.00	0.30	Normal
5	GAMR	Layer moist unit weight, kcf (right-side soil)	0.12	0.10	Normal
6	PHIC	Angle of internal friction, deg (structural wedge soil)	30.00	0.30	Normal
7	WLL	Left-side water elevation, ft	5.00	(0.10)	Normal
8	WLR	Right-side water elevation, ft	1.50	(0.10)	Normal
9	PLO	Point load magnitude, kips	2.00	0.15	Lognormal
10	SMAG	Strip load magnitude, kips/ft	0.80	0.15	Lognormal
11	QRAM	Ramp load magnitude, kips/ft	0.55	0.15	Lognormal

Note: The program RCSLIDE uses non-SI units of measurement. To convert cu ft to cu m, multiply by 0.028. To convert deg to rad, multiply by 0.0175. To convert ft to m, multiply by 0.305. To convert kips to kN, multiply by 4.448. To convert kips/ft to kN/m, multiply by 14.58.

the two sides of the structure are below the structure and are not at the same elevation. Therefore, the safety-factor target should be selected carefully; the larger the target safety factor the better IS performance with a penalty of an increased number of needed simulation cycles.

Table 2 Reliability Results Using Advanced Second Moment (ASM) Method					
X (1)	**Equivalent Normal mean (2)**	**Equivalent Normal stddv (3)**	**Directional Cosine (4)**	**Design Point (5)**	**Partial Safety Factor (6)**
1	0.150000D+00	0.225000D-01	0.720000D-01	0.146306D+00	0.975374D+00
2	0.280000D+02	0.840000D+01	0.690608D+00	0.147723D+02	0.527584D+00
3	0.120000D+00	0.120000D-01	-0.750214D-01	0.122053D+00	0.101711D+01
4	0.280000D+02	0.840000D+01	0.336117D+00	0.122053D+00	0.770076D+00
5	0.120000D+00	0.120000D-01	0.555870D-01	0.118479D+00	0.987325D+00
6	0.300000D+02	0.900000D+01	0.604632D+00	0.175919D+02	0.586396D+00
7	0.500000D+01	0.100000D+01	-0.146174D-01	0.503333D+01	0.100667D+01
8	0.150000D+01	0.100000D+01	-0.336216D-01	0.157666D+01	0.105111D+01
9	0.197787D+01	0.295014D+00	0.000000D+00	0.197787D+01	0.988936D+00
10	0.789299D+00	0.110034D+00	0.128884D+00	0.756962D+00	0.946202D+00
11	0.542957D+00	0.859963D-01	-0.112470D+00	0.565011D+00	0.102729D+01
				Safety factor *SF* =	0.182545D+01
				Reliability index β =	0.228020D+01
				Unsatisfactory performance probability P_u =	0.112980D-01

Table 3 Reliability Results Using Advanced Second Moment (ASM) Method and Monte Carlo Simulation (MCS)		
Reliability Method	**Unsatisfactory Performance Probability P_u**	**Reliability Index β**
ASM	0.112980D-01	0.228020D+01
MCS (50,000 cycles)		
IS01- SF_t =1.0 (seed = -362646)	0.921847D-03	0.311432D+01
IS02- SF_t =1.0 (seed = -4175144)	0.298846D-02	0.274904D+01
IS01- SF_t =1.5 (seed = -362646)	0.123190D-01	0.224703D+01
IS02- SF_t =1.5 (seed = -4175144)	0.103543D-01	0.231326D+01
DR01- SF_t =1.82545 (seed = -362646)	0.096000D-01	0.234162D+01
DR02- SF_t =1.82545 (seed = -4175144)	0.100000D-01	0.232635D+01

This example demonstrated that a nonclosed performance function can be used in the ASM and DR and IS MCS reliability methods. The example also shows the effect of selecting a seed value on the assessed unsatisfactory performance probability.

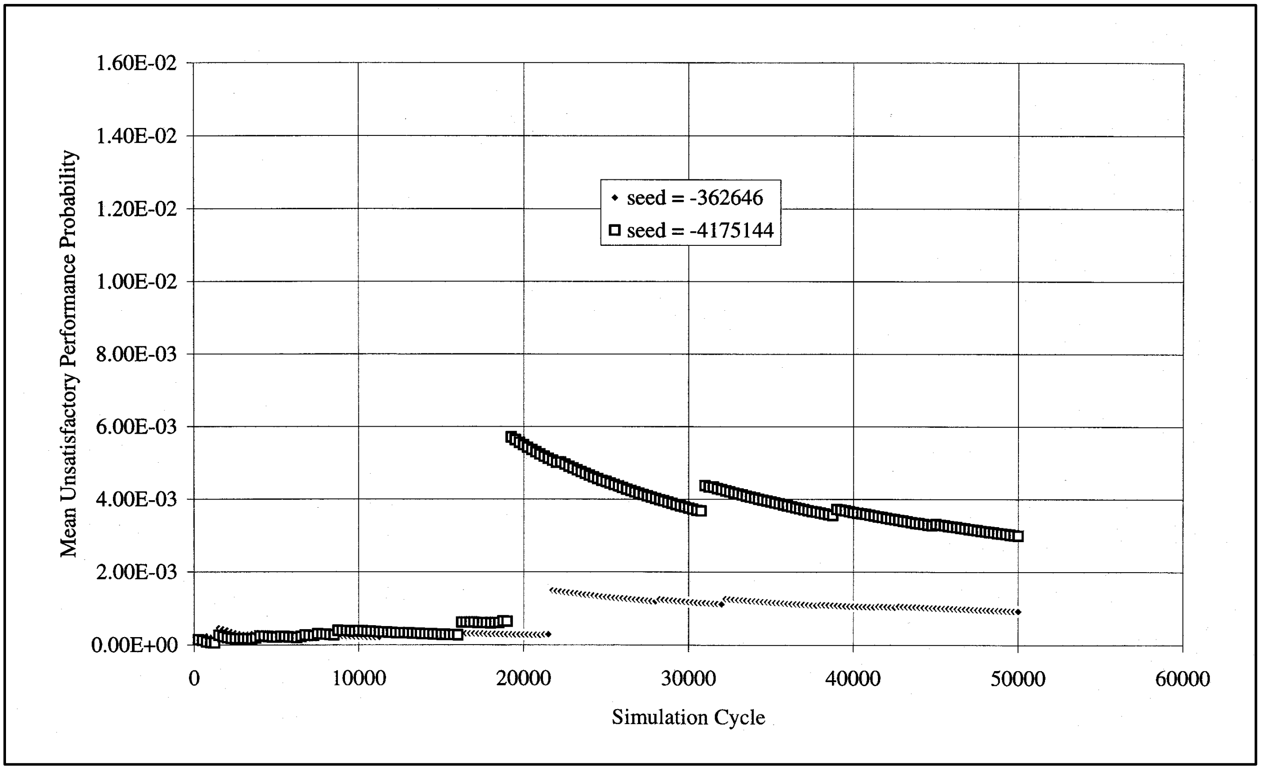

Figure 4. IS with $SF_t = 1.0$

Correlated Random Variables

This case study documents the inclusion of correlated random variables in RCSLIDE and their effects on reliability results. This second example uses the same retaining wall structure as shown in Figure 1; however, different random variables are invoked to fully show the effects of correlated random variables in RCSLIDE.

This case study incorporates negative correlation coefficients between the angle of internal friction ϕ and cohesion *c* values for the right, left, and structural soil layers. The correlation coefficient between ϕ and *c* for this example was determined to be –0.5 and the distribution of ϕ and *c* were considered normally distributed. Note that RCSLIDE requires that distributions for correlated random variables must be normally distributed. This is the default in the RCSLIDE program and the user is alerted to this requirement prior to execution of the reliability program. The characteristics of input random variables are shown in Table 4. The input files for both the CSLIDE and RCSLIDE are shown in Appendix B.

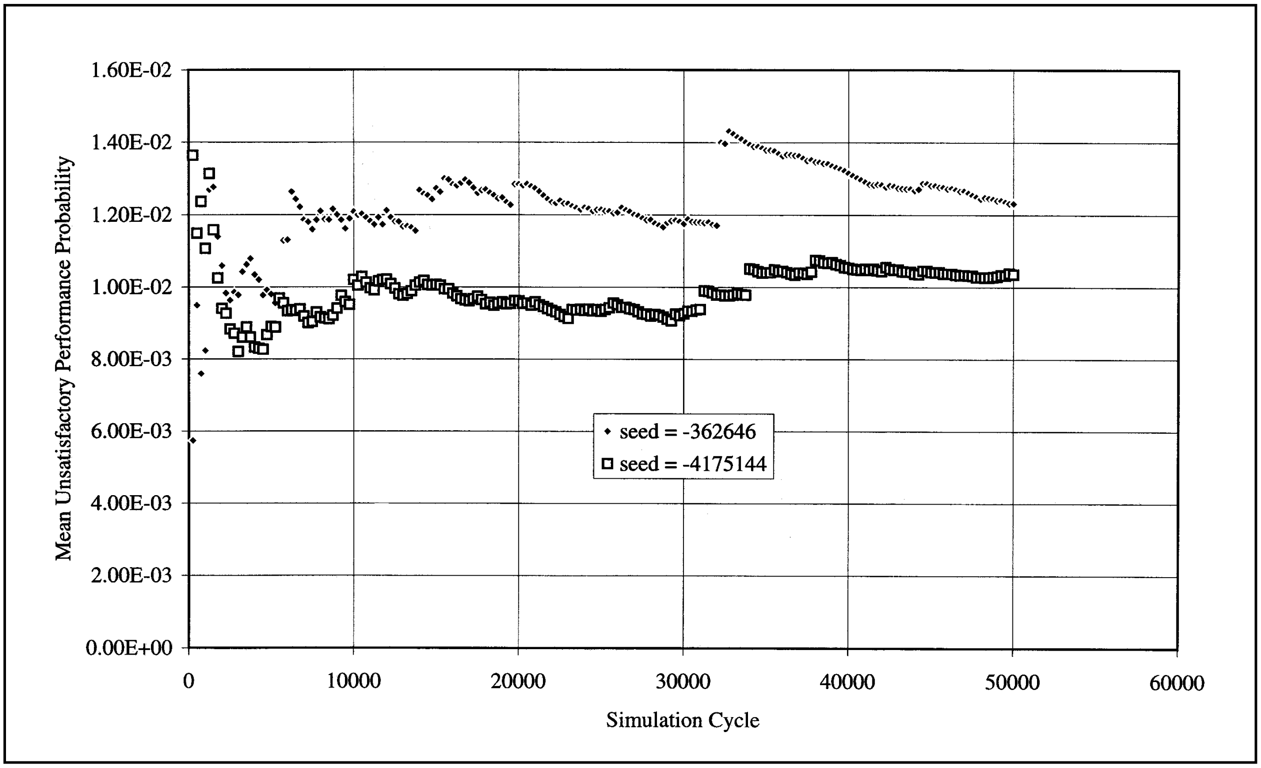

Figure 5. IS with $SF_t = 1.50$

Results of the ASM method for this case study with and without correlation are shown in Tables 5 and 6, respectively. The results show that the use of negative correlation for soil properties, ϕ and c, resulted in a slight change in the reliability index for the gravity structure compared with the reliability index for noncorrelated soil properties.

The results from the direct MCS and IS compared with the correlated ASM are shown in Table 7. The simulation results (direct MCS and IS) are in good agreement with the results of the ASM method. The difference between simulation results (direct MCS and IS) and ASM results is greater for direct MCS than for IS. This can be directly attributed to the relatively small sample size (i.e., simulation cycles) chosen for this example. The complete output from ASM (correlated and noncorrelated), direct MCS, and IS is shown in Appendix B.

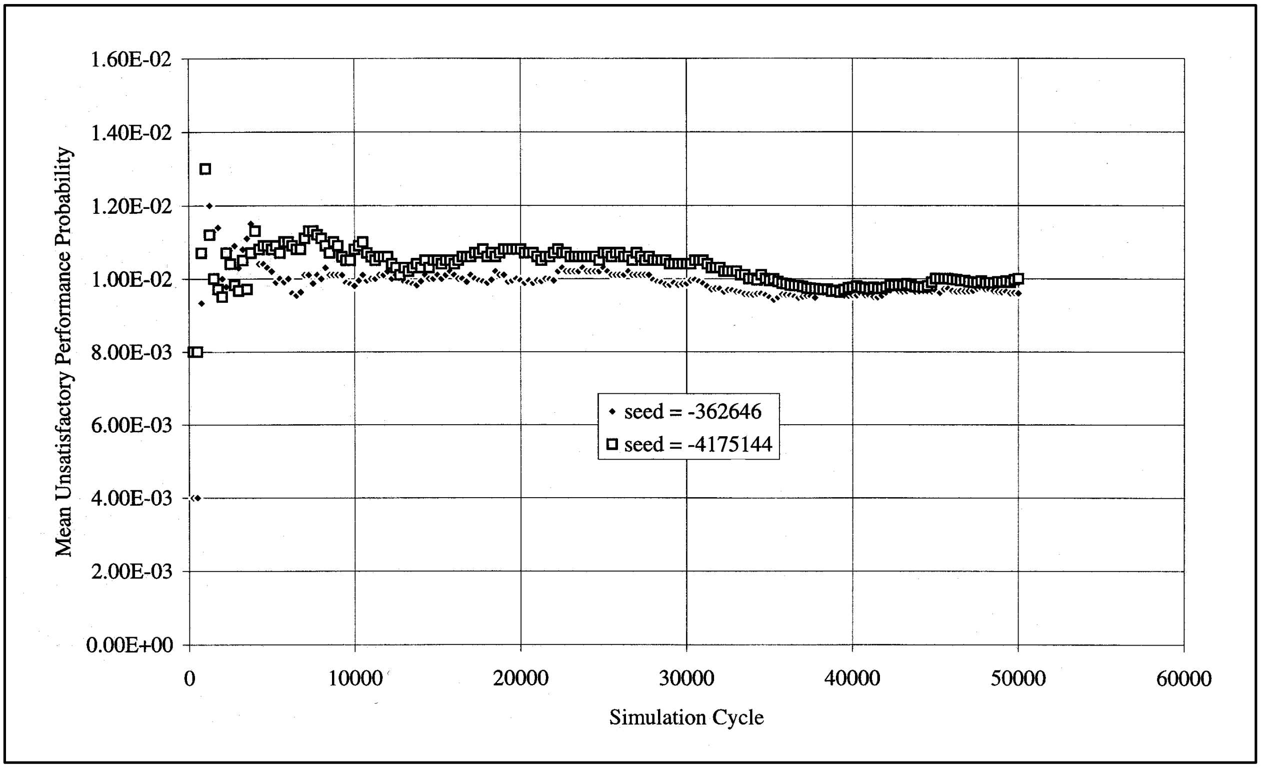

Figure 6. Direct MCS with SF_t = 1.82545

Table 4
Characteristics of Input Random Variables With Correlation

X (1)	Name (2)	Meaning (3)	Mean (4)	COV(Stddv) (5)	Type (6)	Correlation (7)
1	GAMC	Equivalent structure unit weight, kcf	0.15	0.15	Normal	
2	PHIL	Angle of internal friction, deg (left-side soil)	28.00	0.30	Normal	-0.5
3	COSL	Cohesion, ksf (left-side)	0.05	0.2	Normal	
4	GAML	Layer moist unit weight, 1,000 cu ft (left-side soil)	0.12	0.10	Normal	
5	PHIR	Angle of internal friction, deg (right-side)	28.00	0.30	Normal	-0.5
6	COSR	Cohesion, ksf (right-side)	0.05	0.2	Normal	
7	GAMR	Layer moist unit weight, 1,000 cu ft (right-side soil)	0.12	0.10	Normal	
8	PHIC	Angle of internal friction, deg (structural wedge soil)	30.00	0.30	Normal	-0.5
9	COSC	Cohesion, ksf (structural wedge)	0.05	0.2	Normal	
10	WLL	Left-side water elevation, ft	5.00	(0.10)	Normal	
11	WLR	Right-side water elevation, ft	1.50	(0.10)	Normal	

Note: The program RCSLIDE uses non-SI units of measurement. To convert cu ft to cu m, multiply by 0.028. To convert deg to rad, multiply by 0.0175. To convert ft to m, multiply by 0.305. To convert kips to kN, multiply by 4.448. To convert kips/ft to kN/m, multiply by 14.58.

Table 5
Reliability Results Using Advanced Second Moment (ASM) Method With Correlation

X (1)	Equivalent Normal mean (2)	Equivalent Normal stddv (3)	Directional Cosine (4)	Design Point (5)	Partial Safety Factor (6)
1	0.150000D+00	0.225000D-01	0.732600D-01	0.145438D+00	0.969584D+00
2	0.280000D+02	0.840000D+01	0.298147D+00	0.150548D+02	0.537673D+00
3	0.500000D-01	0.100000D-01	0.470781D+00	0.571586D-01	0.114317D+01
4	0.120000D+00	0.120000D-01	-0.202887D+00	0.126739D+00	0.105616D+01
5	0.280000D+02	0.840000D+01	0.167632D+00	0.202051D+02	0.721612D+00
6	0.500000D-01	0.100000D-01	0.290346D+00	0.546398D-01	0.109280D+01
7	0.120000D+00	0.120000D-01	0.768691D-01	0.117447D+00	0.978724D+00
8	0.300000D+02	0.900000D+01	0.362025D-00	0.119634D+02	0.398781D+00
9	0.500000D-01	0.500000D-03	0.627046D+00	0.505010D-01	0.101002D+01
10	0.500000D+01	0.100000D+01	-0.196054D-01	0.505426D+01	0.101085D+01
11	0.100000D+01	0.100000D+01	-0.000000D+00	0.100000D+01	0.100000D+01
				Reliability index β =	0.276785D+01
				Unsatisfactory performance probability P_u =	0.282136D-02

Table 6
Reliability Results Using Advanced Second Moment (ASM) Method Without Correlation

X (1)	Equivalent Normal mean (2)	Equivalent Normal stddv (3)	Directional Cosine (4)	Design Point (5)	Partial Safety Factor (6)
1	0.150000D+00	0.225000D-01	0.501094D-01	0.146978D+00	0.979856D+00
2	0.280000D+02	0.840000D+01	0.644404D+00	0.134931D+02	0.481895D+00
3	0.500000D-01	0.100000D-01	0.364587D-01	0.490229D-01	0.980458D+00
4	0.120000D+00	0.120000D-01	-0.167458D+00	0.125385D+00	0.104488D+01
5	0.280000D+02	0.840000D+01	0.283456D+00	0.216188D+02	0.772100D+00
6	0.500000D-01	0.100000D-01	0.279344D-01	0.492514D-01	0.985027D+00
7	0.120000D+00	0.120000D-01	0.924095D-01	0.117028D+00	0.975234D+00
8	0.300000D+02	0.900000D+01	0.674410D+00	0.137331D+02	0.457770D+00
9	0.500000D-01	0.500000D-03	0.136366D-02	0.499982D-01	0.999963D+00
10	0.500000D+01	0.100000D+01	-0.2884841-01	0.507741D+01	0.101548D+01
11	0.100000D+01	0.100000D+01	-0.867651D-01	0.123253D+01	0.123253D+01
				Reliability index β =	0.268002D+01
				Unsatisfactory performance probability P_u =	0.368090D-02

Table 7
Reliability Results Using Advanced Second Moment (ASM) Method and Monte Carlo Simulation (MCS) With Correlation

Reliability Method	Unsatisfactory Performance Probability P_u	Reliability Index β
ASM	0.282136D-02	0.276785D+01
MCS (3,000 cycles)		
IS- SF_t =1.8 (seed = -9527654)	0.286318D-02	0.276305E+01
DR- SF_t =1.93198 (seed = -1142561)	0.500000D-02	0.257583E+01

6 Conclusions

A methodology based on the safety factor of CSLIDE was developed to assess the structural reliability for concrete retaining walls and gravity structures. This study demonstrates that the structural reliability of concrete retaining walls and gravity structures can be assessed with a nonclosed performance function using the advanced second moment (ASM) method, direct (DR) Monte Carlo simulation (MCS), and importance sampling (IS). Correlated and noncorrelated random variables were considered in this study.

The importance sampling simulation requires a user-defined target safety factor that is used to shift the mean values of the basic random variables. In this case, the design point is not necessarily a good choice for shifting the mean values, nor is a target safety factor of one. The safety factor target should be selected carefully; the larger the target safety factor, the better IS performance with a penalty of an increased number of simulation cycles needed. Importance sampling in reliability assessment needs to be carefully employed and compared with other methods. On the contrary, direct MCS is quite good, but with the disadvantage of possibly a large number of simulation cycles in order to achieve an accurate estimated unsatisfactory performance probability for structural stability.

Case studies were used to demonstrate utilizing a nonclosed performance function in conjunction with the ASM and DR and IS MCS reliability methods. The example also shows the effect of selecting a seed value and a target safety factor on the assessed unsatisfactory performance probability. In addition, the effect of correlation of random variables was examined.

7 Recommended Future Work

In this study, a methodology and software for the stability and reliability assessment of gravity concrete structures were developed. The software development procedure described in this study is significant because it establishes a prototype reliability software that is modular and based on an existing CASE program. Other CASE programs can be modified and utilized for reliability purposes in a similar fashion. The following recommendations are provided:

a. Case studies and software testing. Case studies using RCSLIDE need to be developed. Software testing can also be performed.

b. Variable arrays and their values. In the process of reliability assessment, the input random variables used by CSLIDE and the safety factor obtained from CSLIDE were not directly passed to the performance function in reliability modules, ASM and MCS. Therefore, speed and the accuracy in numerical computations were somewhat compromised. Increased speed and accuracy in numerical computations without the loss of flexibility for each module is needed.

c. System integration and help menu. The CSLIDE program needs to be integrated with the reliability programs resulting in one integrated FORTRAN program. The result will enhance speed and performance. The integrated program will still be executed from the Microsoft Visual BASIC shell.

d. Help. To reach a truly user-friendly interface, a hypertext-format-on-line help manual needs to be developed instead of the current text format help. The help capabilities can be improved to allow for word searching. Also, the help file can be converted to a semi or full hypertext format according to Microsoft Visual BASIC software.

e. Converters or filters and graphics. Some existing input data files for CSLIDE use *free* format and cannot be used directly in the reliability assessment computer software RCSLIDE, which uses formatted input data as shown in Appendix A. A filter program for converting the free format data to formatted data is needed to develop and facilitate the usage of RCSLIDE. A filter or converter can be developed to read existing

CSLIDE input files and save them in the RCSLIDE format. The filter will read an existing input file using an alphanumeric format, and then will strip it to its individual components, which will be placed at the correct locations in fields of RCSLIDE. The graphical capabilities of RCSLIDE can be improved to include plotting results from its output file. For example, pressure distributions and forces can be added.

f. *Soil properties.* Modeling correlated soil properties should be improved by developing and implementing cases involving lognormal distributions, with and without normal distributions, for soil strength parameters such as angle of internal friction and cohesion since analytical solution methods exist in this case. Also, the nonlinear relationships for soil strength properties should be developed and implemented in CSLIDE instead of using soil strength parameters. Then RCSLIDE can be revised accordingly.

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Appendix A
Input and Output Data for Case Study 1

Input Data for CSLIDE

```
START
001 TITL Title Problem-1
002 TITL
003 TITL
004 TITL
005 STRU  8  1.500000E-01  0.000000E+00  1.000000E+00
006     0.00     0.00
007     0.00     2.00
008     6.00     2.00
009     6.00    14.00
010     8.00    14.00
011     8.00     2.00
012    12.00     2.00
013    12.00     0.00
014 SOLT  1  1 2.800000E+01 0.000000E+00 1.200000E-01 1.400000E+01
0.000000E+00
015  -500.00    14.00
016 SORT  1  1 2.800000E+01 0.000000E+00 1.200000E-01 4.000000E+00
0.000000E+00
017   500.00     4.00
018 SOST  3.000000E+01  0.000000E+00  0.000000E+00
019 METH  1
020 WATR  5.000000E+00  1.500000E+00  6.250000E-02  -1
021 FACT     0.5000     1.5000     1.0000
022 VPLO       22.0000  2.000000E+00
023 VSLO       10.0000        8.0000  8.000000E-01
024 VRLO        6.0000        9.0000  5.500000E-01
025 END
```

Input Data for Reliability Methods

```
TITL  Title ASM-1b01
STRU0001  1.500000E-01  1.500000E-01 C NOR
SOLT0103  2.800000E+01  3.000000E-01 C NOR
SOLT0105  1.200000E-01  1.000000E-01 C NOR
SORT0103  2.800000E+01  3.000000E-01 C NOR
SORT0105  1.200000E-01  1.000000E-01 C NOR
SOST0003  3.000000E+01  3.000000E-01 C NOR
WATR0001  5.000000E+00  1.000000E+00 S NOR
WATR0002  1.500000E+00  1.000000E+00 S NOR
VPLO0105  2.000000E+00  1.500000E-01 C LOG
```

```
VSLO0105  8.000000E-01  1.500000E-01 C LOG
VRLO0105  5.500000E-01  1.500000E-01 C LOG
END
```

Output of Advanced Second Moment (ASM) Method

```
Title =   Title ASM-1b01
Total number of random variables =   11

***** The input data *****

-x=rv- --name-- ----mean---- ---Sigma---- ----cov----- code Type
X(  1) STRU 0 1  .150000D+00  .225000D-01  .150000D+00    C  NOR
X(  2) SOLT 1 3  .280000D+02  .840000D+01  .300000D+00    C  NOR
X(  3) SOLT 1 5  .120000D+00  .120000D-01  .100000D+00    C  NOR
X(  4) SORT 1 3  .280000D+02  .840000D+01  .300000D+00    C  NOR
X(  5) SORT 1 5  .120000D+00  .120000D-01  .100000D+00    C  NOR
X(  6) SOST 0 3  .300000D+02  .900000D+01  .300000D+00    C  NOR
X(  7) WATR 0 1  .500000D+01  .100000D+01  .200000D+00    S  NOR
X(  8) WATR 0 2  .150000D+01  .100000D+01  .666667D+00    S  NOR
X(  9) VPLO 1 5  .200000D+01  .300000D+00  .150000D+00    C  LOG
X( 10) VSLO 1 5  .800000D+00  .120000D+00  .150000D+00    C  LOG
X( 11) VRLO 1 5  .550000D+00  .825000D-01  .150000D+00    C  LOG

The tolerance of reliability index (beta)    = .100000D-01
The ratio of dx/x for random variables       = .100000D-02
The max. iterations for finding beta         = 10
The increment for finding beta               =   .2500
The 1=absolute 2=relative tolerance for beta =  2

The limit state Z=R-L=L(SF-1) or Z=SF-1

***** The result *****


The iteration No. = 1
-i ---meanEN--- ----stdEN--- ---alpha---- -----dp----- -Partial.SF-
 1  .150000D+00  .225000D-01  .105081D+00  .144587D+00  .963915D+00
 2  .280000D+02  .840000D+01  .639212D+00  .157077D+02  .560990D+00
 3  .120000D+00  .120000D-01 -.119625D+00  .123286D+00  .102739D+01
 4  .280000D+02  .840000D+01  .329423D+00  .216651D+02  .773753D+00
 5  .120000D+00  .120000D-01  .671452D-01  .118155D+00  .984628D+00
 6  .300000D+02  .900000D+01  .611215D+00  .174066D+02  .580219D+00
 7  .500000D+01  .100000D+01 -.542979D-01  .512431D+01  .102486D+01
 8  .150000D+01  .100000D+01 -.896885D-01  .170533D+01  .113688D+01
 9  .197775D+01  .298333D+00  .000000D+00  .197775D+01  .988875D+00
10  .791100D+00  .119333D+00  .195616D+00  .737659D+00  .922074D+00
11  .543881D+00  .820415D-01 -.173740D+00  .576513D+00  .104821D+01
The reliability index (beta) =  .228933D+01

The iteration No. = 2
-i ---meanEN--- ----stdEN--- ---alpha---- -----dp----- -Partial.SF-
 1  .150000D+00  .225000D-01  .720000D-01  .146306D+00  .975374D+00
 2  .280000D+02  .840000D+01  .690608D+00  .147723D+02  .527584D+00
 3  .120000D+00  .120000D-01 -.750214D-01  .122053D+00  .101711D+01
 4  .280000D+02  .840000D+01  .336117D+00  .215621D+02  .770076D+00
 5  .120000D+00  .120000D-01  .555870D-01  .118479D+00  .987325D+00
 6  .300000D+02  .900000D+01  .604632D+00  .175919D+02  .586396D+00
 7  .500000D+01  .100000D+01 -.146174D-01  .503333D+01  .100667D+01
 8  .150000D+01  .100000D+01 -.336216D-01  .157666D+01  .105111D+01
 9  .197787D+01  .295014D+00  .000000D+00  .197787D+01  .988936D+00
10  .789299D+00  .110034D+00  .128884D+00  .756962D+00  .946202D+00
11  .542957D+00  .859963D-01 -.112470D+00  .565011D+00  .102729D+01
The reliability index (beta) =  .228020D+01

The unsatisfactory performance probability =  .112980D-01
```

Output of Importance Sampling - IS01 (SF_t =1.0)

```
Title =   Title ASM-1b01
Total number of random variables =   11

***** The input data *****

-x=rv- --name-- ----mean---- ---Sigma---- ----cov----- code Type
X(  1) STRU 0 1  .150000D+00  .225000D-01  .150000D+00    C  NOR
X(  2) SOLT 1 3  .280000D+02  .840000D+01  .300000D+00    C  NOR
X(  3) SOLT 1 5  .120000D+00  .120000D-01  .100000D+00    C  NOR
X(  4) SORT 1 3  .280000D+02  .840000D+01  .300000D+00    C  NOR
X(  5) SORT 1 5  .120000D+00  .120000D-01  .100000D+00    C  NOR
X(  6) SOST 0 3  .300000D+02  .900000D+01  .300000D+00    C  NOR
X(  7) WATR 0 1  .500000D+01  .100000D+01  .200000D+00    S  NOR
X(  8) WATR 0 2  .150000D+01  .100000D+01  .666667D+00    S  NOR
X(  9) VPLO 1 5  .200000D+01  .300000D+00  .150000D+00    C  LOG
X( 10) VSLO 1 5  .800000D+00  .120000D+00  .150000D+00    C  LOG
X( 11) VRLO 1 5  .550000D+00  .825000D-01  .150000D+00    C  LOG

Tolerance for root finding in beta        = .100000D-01
Tolerance for finding dz/dx of general rv = .100000D-02
Max. iterations for finding safety index  = 10

The limit state Z=R-L=L(SF-1)

***** The result *****


The simulation cycle    =        50000
The initial given  seed =            0
The sensitivity test ratio         =  .100000D+00
The target safety factor           =  .100000D+00
The initial output cycle increment =          500

<<< The sensitivity result >>>

The safety factor (SF) =  .182545E+01

-x=rv- --Name-- --M=Mean-- SF1:M* .90 SF2:M*1.10 --SF1-SF- --SF2-SF-- --
Sense.--
X(  1) STRU 0 1  .1500D+00  .1796D+01  .1854D+01 -.2896D-01  .2886D-01
.9000D+00
X(  2) SOLT 1 3  .2800D+02  .1739D+01  .1915D+01 -.8680D-01  .8926D-01
.9000D+00
X(  3) SOLT 1 5  .1200D+00  .1878D+01  .1779D+01  .5298D-01 -.4615D-01
.1100D+01
X(  4) SORT 1 3  .2800D+02  .1782D+01  .1872D+01 -.4390D-01  .4684D-01
.9000D+00
X(  5) SORT 1 5  .1200D+00  .1798D+01  .1853D+01 -.2758D-01  .2781D-01
.9000D+00
X(  6) SOST 0 3  .3000D+02  .1743D+01  .1912D+01 -.8206D-01  .8633D-01
.9000D+00
X(  7) WATR 0 1  .5000D+01  .1837D+01  .1814D+01  .1117D-01 -.1126D-01
.1100D+01
X(  8) WATR 0 2  .1500D+01  .1831D+01  .1820D+01  .5501D-02 -.5618D-02
.1100D+01
X(  9) VPLO 1 5  .2000D+01  .1825D+01  .1825D+01  .0000D+00  .0000D+00
.1000D+01
X( 10) VSLO 1 5  .8000D+00  .1772D+01  .1880D+01 -.5366D-01  .5458D-01
.9000D+00
X( 11) VRLO 1 5  .5500D+00  .1876D+01  .1779D+01  .5020D-01 -.4611D-01
.1100D+01


<<< The shifted means >>>
-x=rv- --Name-- ---M=Mean--- Shifted.Mean ---Ratio----
X(  1) STRU 0 1  .150000D+00  .109350D+00  .729000D+00
X(  2) SOLT 1 3  .280000D+02  .204120D+02  .729000D+00
X(  3) SOLT 1 5  .120000D+00  .159720D+00  .133100D+01
X(  4) SORT 1 3  .280000D+02  .204120D+02  .729000D+00
X(  5) SORT 1 5  .120000D+00  .874800D-01  .729000D+00
```

```
X(  6) SOST 0 3  .300000D+02  .218700D+02  .729000D+00
X(  7) WATR 0 1  .500000D+01  .665500D+01  .133100D+01
X(  8) WATR 0 2  .150000D+01  .199650D+01  .133100D+01
X(  9) VPLO 1 5  .200000D+01  .200000D+01  .100000D+01
X( 10) VSLO 1 5  .800000D+00  .583200D+00  .729000D+00
X( 11) VRLO 1 5  .550000D+00  .732050D+00  .133100D+01

The safety factor =  .930955D+00
The iteration of shifting =    3
The initial random seed =      -362646

*** The result of importance sampling simulation ***

=========================
No.of.cycle- -ave.cum.Pu-
------------ ------------
         500  .100956E-03
        1000  .196125E-03
        1500  .456397E-03
        2000  .396067E-03
        2500  .322244E-03
        3000  .274498E-03
        3500  .292017E-03
        4000  .289559E-03
        4500  .266437E-03
        5000  .241174E-03
        5500  .242164E-03
        6000  .295676E-03
        6500  .309899E-03
        7000  .289754E-03
        7500  .279749E-03
        8000  .275022E-03
        8500  .259333E-03
        9000  .245442E-03
        9500  .234040E-03
       10000  .223853E-03
       10500  .214773E-03
       11000  .207800E-03
       11500  .293170E-03
       12000  .296667E-03
       12500  .288635E-03
       13000  .350232E-03
       13500  .339149E-03
       14000  .334743E-03
       14500  .342194E-03
       15000  .331299E-03
       15500  .321954E-03
       16000  .315085E-03
       16500  .310017E-03
       17000  .311496E-03
       17500  .303805E-03
       18000  .295958E-03
       18500  .295868E-03
       19000  .288948E-03
       19500  .281823E-03
       20000  .280597E-03
       20500  .275871E-03
       21000  .269890E-03
       21500  .290372E-03
       22000  .147684E-02
       22500  .144566E-02
       23000  .141676E-02
       23500  .139081E-02
       24000  .136250E-02
       24500  .133629E-02
       25000  .130982E-02
       25500  .129265E-02
       26000  .127804E-02
       26500  .125415E-02
       27000  .123323E-02
       27500  .121099E-02
       28000  .118997E-02
       28500  .123509E-02
```

```
       29000  .121432E-02
       29500  .119612E-02
       30000  .117662E-02
       30500  .115807E-02
       31000  .114949E-02
       31500  .113138E-02
       32000  .111411E-02
       32500  .125021E-02
       33000  .123166E-02
       33500  .121409E-02
       34000  .119670E-02
       34500  .117969E-02
       35000  .116477E-02
       35500  .114886E-02
       36000  .113348E-02
       36500  .111863E-02
       37000  .110425E-02
       37500  .108955E-02
       38000  .110085E-02
       38500  .108839E-02
       39000  .107457E-02
       39500  .106399E-02
       40000  .105695E-02
       40500  .104511E-02
       41000  .104004E-02
       41500  .105100E-02
       42000  .103884E-02
       42500  .102745E-02
       43000  .104360E-02
       43500  .103304E-02
       44000  .102611E-02
       44500  .101544E-02
       45000  .100652E-02
       45500  .995545E-03
       46000  .990373E-03
       46500  .980915E-03
       47000  .971398E-03
       47500  .961226E-03
       48000  .952945E-03
       48500  .943868E-03
       49000  .934695E-03
       49500  .925331E-03
       50000  .921847E-03
=========================

The importance failure count =       28770

The safety factor > 10 count =         277

The reliability index        = .311432D+01

The binomial statitics
The ave of    Pu    (AvePu)  = .921847D-03
The var of avePu (varAvePu)  = .184199D-07
The std of avePu (stdAvePu)  = .135720D-03
The cov of avePu (covAvePu)  = .147226D+00


The simulation and sample mean statistics
The ave of    Pu    (avePu)  = .921847D-03
The var of    Pu    (varPu)b = .144235D-01
The var of    Pu    (varPu)  = .144238D-01
The std of    Pu    (stdPu)  = .120099D+00
The cov of    Pu    (covPu)  = .130281D+03
The var of avePu (varAvePu)b = .288470D-06
The var of avePu (varAvePu)  = .288476D-06
The std of avePu (stdAvePu)  = .537099D-03
The cov of avePu (covAvePu)  = .582634D+00
b = biased, for variance computation using the sample size N.
```

Output of Importance Sampling - IS02 (SF_t =1.0)

```
Title =   Title ASM-1b01
Total number of random variables =   11

***** The input data *****

-x=rv- --name-- ----mean---- ---Sigma---- ----cov----- code Type
X(  1) STRU 0 1  .150000D+00  .225000D-01  .150000D+00    C  NOR
X(  2) SOLT 1 3  .280000D+02  .840000D+01  .300000D+00    C  NOR
X(  3) SOLT 1 5  .120000D+00  .120000D-01  .100000D+00    C  NOR
X(  4) SORT 1 3  .280000D+02  .840000D+01  .300000D+00    C  NOR
X(  5) SORT 1 5  .120000D+00  .120000D-01  .100000D+00    C  NOR
X(  6) SOST 0 3  .300000D+02  .900000D+01  .300000D+00    C  NOR
X(  7) WATR 0 1  .500000D+01  .100000D+01  .200000D+00    S  NOR
X(  8) WATR 0 2  .150000D+01  .100000D+01  .666667D+00    S  NOR
X(  9) VPLO 1 5  .200000D+01  .300000D+00  .150000D+00    C  LOG
X( 10) VSLO 1 5  .800000D+00  .120000D+00  .150000D+00    C  LOG
X( 11) VRLO 1 5  .550000D+00  .825000D-01  .150000D+00    C  LOG

The limit state Z=R-L=L(SF-1)

***** The result *****


The simulation cycle    =        50000
The initial given  seed =            0
The sensitivity test ratio           =  .100000D+00
The target safety factor             =  .100000D+00
The initial output cycle increment   =          500

<<< The sensitivity result >>>

The safety factor (SF) =  .182545E+01

-x=rv- --Name-- --M=Mean-- SF1:M* .90 SF2:M*1.10 --SF1-SF-- --SF2-SF-- --
Sense.--
X(  1) STRU 0 1  .1500D+00  .1796D+01  .1854D+01 -.2896D-01  .2886D-01
.9000D+00
X(  2) SOLT 1 3  .2800D+02  .1739D+01  .1915D+01 -.8680D-01  .8926D-01
.9000D+00
X(  3) SOLT 1 5  .1200D+00  .1878D+01  .1779D+01  .5298D-01 -.4615D-01
.1100D+01
X(  4) SORT 1 3  .2800D+02  .1782D+01  .1872D+01 -.4390D-01  .4684D-01
.9000D+00
X(  5) SORT 1 5  .1200D+00  .1798D+01  .1853D+01 -.2758D-01  .2781D-01
.9000D+00
X(  6) SOST 0 3  .3000D+02  .1743D+01  .1912D+01 -.8206D-01  .8633D-01
.9000D+00
X(  7) WATR 0 1  .5000D+01  .1837D+01  .1814D+01  .1117D-01 -.1126D-01
.1100D+01
X(  8) WATR 0 2  .1500D+01  .1831D+01  .1820D+01  .5501D-02 -.5618D-02
.1100D+01
X(  9) VPLO 1 5  .2000D+01  .1825D+01  .1825D+01  .0000D+00  .0000D+00
.1000D+01
X( 10) VSLO 1 5  .8000D+00  .1772D+01  .1880D+01 -.5366D-01  .5458D-01
.9000D+00
X( 11) VRLO 1 5  .5500D+00  .1876D+01  .1779D+01  .5020D-01 -.4611D-01
.1100D+01


<<< The shifted means >>>
-x=rv- --Name-- ---M=Mean--- Shifted.Mean ---Ratio----
X(  1) STRU 0 1  .150000D+00  .109350D+00  .729000D+00
X(  2) SOLT 1 3  .280000D+02  .204120D+02  .729000D+00
X(  3) SOLT 1 5  .120000D+00  .159720D+00  .133100D+01
X(  4) SORT 1 3  .280000D+02  .204120D+02  .729000D+00
X(  5) SORT 1 5  .120000D+00  .874800D-01  .729000D+00
X(  6) SOST 0 3  .300000D+02  .218700D+02  .729000D+00
X(  7) WATR 0 1  .500000D+01  .665500D+01  .133100D+01
X(  8) WATR 0 2  .150000D+01  .199650D+01  .133100D+01
X(  9) VPLO 1 5  .200000D+01  .200000D+01  .100000D+01
```

```
X( 10) VSLO 1 5  .800000D+00  .583200D+00  .729000D+00
X( 11) VRLO 1 5  .550000D+00  .732050D+00  .133100D+01

The safety factor =  .930955D+00
The iteration of shifting =    3
The initial random seed =     -4175144

*** The result of importance sampling simulation ***

=========================
No.of.cycle- -ave.cum.Pu-
------------ ------------
         500  .119824E-03
        1000  .629463E-04
        1500  .261312E-03
        2000  .197144E-03
        2500  .168649E-03
        3000  .173870E-03
        3500  .157569E-03
        4000  .236490E-03
        4500  .227291E-03
        5000  .209060E-03
        5500  .224515E-03
        6000  .206776E-03
        6500  .227723E-03
        7000  .259903E-03
        7500  .301265E-03
        8000  .285042E-03
        8500  .269437E-03
        9000  .387376E-03
        9500  .376566E-03
       10000  .385317E-03
       10500  .367690E-03
       11000  .357962E-03
       11500  .346093E-03
       12000  .334930E-03
       12500  .325378E-03
       13000  .322924E-03
       13500  .313199E-03
       14000  .302524E-03
       14500  .292869E-03
       15000  .283279E-03
       15500  .274190E-03
       16000  .268454E-03
       16500  .620358E-03
       17000  .615184E-03
       17500  .605702E-03
       18000  .592766E-03
       18500  .607881E-03
       19000  .639766E-03
       19500  .563074E-02
       20000  .549124E-02
       20500  .536162E-02
       21000  .523449E-02
       21500  .511659E-02
       22000  .500623E-02
       22500  .496222E-02
       23000  .485512E-02
       23500  .475240E-02
       24000  .465357E-02
       24500  .456086E-02
       25000  .448282E-02
       25500  .439813E-02
       26000  .431716E-02
       26500  .423777E-02
       27000  .416161E-02
       27500  .408825E-02
       28000  .401980E-02
       28500  .394970E-02
       29000  .388260E-02
       29500  .381746E-02
       30000  .375398E-02
       30500  .369433E-02
```

```
       31000  .437118E-02
       31500  .432964E-02
       32000  .426240E-02
       32500  .420035E-02
       33000  .414427E-02
       33500  .408270E-02
       34000  .403066E-02
       34500  .397249E-02
       35000  .392409E-02
       35500  .386926E-02
       36000  .381591E-02
       36500  .376435E-02
       37000  .371404E-02
       37500  .366497E-02
       38000  .362055E-02
       38500  .357532E-02
       39000  .372158E-02
       39500  .367979E-02
       40000  .363453E-02
       40500  .360308E-02
       41000  .356096E-02
       41500  .351836E-02
       42000  .347662E-02
       42500  .343614E-02
       43000  .339885E-02
       43500  .336030E-02
       44000  .332577E-02
       44500  .328947E-02
       45000  .330596E-02
       45500  .327190E-02
       46000  .323804E-02
       46500  .320370E-02
       47000  .316994E-02
       47500  .313851E-02
       48000  .310588E-02
       48500  .307394E-02
       49000  .304727E-02
       49500  .301671E-02
       50000  .298846E-02
=========================

The importance failure count =       28881

The safety factor > 10 count =         267

The reliability index        = .274904D+01

The binomial statistics
The ave of    Pu    (AvePu)  = .298846D-02
The var of avePu (varAvePu)  = .595906D-07
The std of avePu (stdAvePu)  = .244112D-03
The cov of avePu (covAvePu)  = .816848D-01


The simulation and sample mean statistics
The ave of    Pu    (avePu)  = .298846D-02
The var of    Pu    (varPu)b = .202745D+00
The var of    Pu    (varPu)  = .202749D+00
The std of    Pu    (stdPu)  = .450276D+00
The cov of    Pu    (covPu)  = .150672D+03
The var of avePu (varAvePu)b = .405490D-05
The var of avePu (varAvePu)  = .405498D-05
The std of avePu (stdAvePu)  = .201370D-02
The cov of avePu (covAvePu)  = .673824D+00
b = biased, for variance computation using the sample size N.
```

Output of Importance Sampling - IS01 (SF_t =1.5)

```
Title =   Title ASM-1b01
Total number of random variables =   11

***** The input data *****

-x=rv- --name-- ----mean---- ---Sigma---- ----cov----- code Type
X(  1) STRU 0 1  .150000D+00  .225000D-01  .150000D+00    C  NOR
X(  2) SOLT 1 3  .280000D+02  .840000D+01  .300000D+00    C  NOR
X(  3) SOLT 1 5  .120000D+00  .120000D-01  .100000D+00    C  NOR
X(  4) SORT 1 3  .280000D+02  .840000D+01  .300000D+00    C  NOR
X(  5) SORT 1 5  .120000D+00  .120000D-01  .100000D+00    C  NOR
X(  6) SOST 0 3  .300000D+02  .900000D+01  .300000D+00    C  NOR
X(  7) WATR 0 1  .500000D+01  .100000D+01  .200000D+00    S  NOR
X(  8) WATR 0 2  .150000D+01  .100000D+01  .666667D+00    S  NOR
X(  9) VPLO 1 5  .200000D+01  .300000D+00  .150000D+00    C  LOG
X( 10) VSLO 1 5  .800000D+00  .120000D+00  .150000D+00    C  LOG
X( 11) VRLO 1 5  .550000D+00  .825000D-01  .150000D+00    C  LOG

The limit state Z=R-L=L(SF-1) or Z=SF-1

The simulation cycle    =        50000
The initial given  seed =      -362646
The sensitivity test ratio         =  .100000D+00
The target safety factor           =  .150000D+01
The initial output cycle increment =            0

<<< The sensitivity result >>>

The safety factor (SF) =  .182545E+01

-x=rv- --Name-- --M=Mean-- SF1:M* .90 SF2:M*1.10 --SF1-SF- --SF2-SF-- --
Sense.--
X(  1) STRU 0 1  .1500D+00  .1796D+01  .1854D+01 -.2896D-01  .2886D-01
.9000D+00
X(  2) SOLT 1 3  .2800D+02  .1739D+01  .1915D+01 -.8680D-01  .8926D-01
.9000D+00
X(  3) SOLT 1 5  .1200D+00  .1878D+01  .1779D+01  .5298D-01 -.4615D-01
.1100D+01
X(  4) SORT 1 3  .2800D+02  .1782D+01  .1872D+01 -.4390D-01  .4684D-01
.9000D+00
X(  5) SORT 1 5  .1200D+00  .1798D+01  .1853D+01 -.2758D-01  .2781D-01
.9000D+00
X(  6) SOST 0 3  .3000D+02  .1743D+01  .1912D+01 -.8206D-01  .8633D-01
.9000D+00
X(  7) WATR 0 1  .5000D+01  .1837D+01  .1814D+01  .1117D-01 -.1126D-01
.1100D+01
X(  8) WATR 0 2  .1500D+01  .1831D+01  .1820D+01  .5501D-02 -.5618D-02
.1100D+01
X(  9) VPLO 1 5  .2000D+01  .1825D+01  .1825D+01  .0000D+00  .0000D+00
.1000D+01
X( 10) VSLO 1 5  .8000D+00  .1772D+01  .1880D+01 -.5366D-01  .5458D-01
.9000D+00
X( 11) VRLO 1 5  .5500D+00  .1876D+01  .1779D+01  .5020D-01 -.4611D-01
.1100D+01


<<< The shifted means >>>
-x=rv- --Name-- ---M=Mean--- Shifted.Mean ---Ratio----
X(  1) STRU 0 1  .150000D+00  .135000D+00  .900000D+00
X(  2) SOLT 1 3  .280000D+02  .252000D+02  .900000D+00
X(  3) SOLT 1 5  .120000D+00  .132000D+00  .110000D+01
X(  4) SORT 1 3  .280000D+02  .252000D+02  .900000D+00
X(  5) SORT 1 5  .120000D+00  .108000D+00  .900000D+00
X(  6) SOST 0 3  .300000D+02  .270000D+02  .900000D+00
X(  7) WATR 0 1  .500000D+01  .550000D+01  .110000D+01
X(  8) WATR 0 2  .150000D+01  .165000D+01  .110000D+01
X(  9) VPLO 1 5  .200000D+01  .200000D+01  .100000D+01
X( 10) VSLO 1 5  .800000D+00  .720000D+00  .900000D+00
X( 11) VRLO 1 5  .550000D+00  .605000D+00  .110000D+01
```

```
The safety factor =  .143618D+01
The iteration of shifting =    1

***** The result *****

The revised output cycle increment =          500

*** The result of importance sampling simulation ***

=========================
No.of.cycle- -ave.cum.Pu-
------------ ------------
         500  .949377E-02
        1000  .823076E-02
        1500  .127657E-01
        2000  .105944E-01
        2500  .963586E-02
        3000  .977791E-02
        3500  .106235E-01
        4000  .103422E-01
        4500  .977378E-02
        5000  .979711E-02
        5500  .966660E-02
        6000  .113069E-01
        6500  .124313E-01
        7000  .118592E-01
        7500  .115973E-01
        8000  .121058E-01
        8500  .118632E-01
        9000  .120089E-01
        9500  .116215E-01
       10000  .120883E-01
       10500  .120262E-01
       11000  .118223E-01
       11500  .119256E-01
       12000  .121193E-01
       12500  .118127E-01
       13000  .116685E-01
       13500  .116430E-01
       14000  .126775E-01
       14500  .125351E-01
       15000  .127253E-01
       15500  .129989E-01
       16000  .128307E-01
       16500  .128825E-01
       17000  .128826E-01
       17500  .126003E-01
       18000  .126962E-01
       18500  .125403E-01
       19000  .124761E-01
       19500  .122777E-01
       20000  .128463E-01
       20500  .128484E-01
       21000  .127292E-01
       21500  .125329E-01
       22000  .123501E-01
       22500  .123911E-01
       23000  .123040E-01
       23500  .121881E-01
       24000  .122018E-01
       24500  .121061E-01
       25000  .121410E-01
       25500  .120981E-01
       26000  .120675E-01
       26500  .121282E-01
       27000  .119992E-01
       27500  .119030E-01
       28000  .118618E-01
       28500  .117067E-01
       29000  .117883E-01
       29500  .118460E-01
       30000  .117547E-01
       30500  .118110E-01
```

```
       31000  .117999E-01
       31500  .117988E-01
       32000  .117074E-01
       32500  .139721E-01
       33000  .142307E-01
       33500  .140911E-01
       34000  .139402E-01
       34500  .138819E-01
       35000  .137882E-01
       35500  .137614E-01
       36000  .136297E-01
       36500  .136593E-01
       37000  .136282E-01
       37500  .134956E-01
       38000  .134633E-01
       38500  .134175E-01
       39000  .133462E-01
       39500  .132598E-01
       40000  .131473E-01
       40500  .130197E-01
       41000  .129080E-01
       41500  .128247E-01
       42000  .128265E-01
       42500  .128098E-01
       43000  .127428E-01
       43500  .127139E-01
       44000  .126756E-01
       44500  .128702E-01
       45000  .128092E-01
       45500  .127654E-01
       46000  .127176E-01
       46500  .126982E-01
       47000  .126593E-01
       47500  .125463E-01
       48000  .124464E-01
       48500  .124563E-01
       49000  .123950E-01
       49500  .123531E-01
       50000  .123190E-01
=========================

The importance failure count =        4035

The safety factor > 10 count =          37

The reliability index        = .224703D+01

The binomial statistics
The ave of    Pu    (AvePu)  = .123190D-01
The var of avePu (varAvePu)  = .243344D-06
The std of avePu (stdAvePu)  = .493299D-03
The cov of avePu (covAvePu)  = .400439D-01


The simulation and sample mean statistics
The ave of    Pu    (avePu)  = .123190D-01
The var of    Pu    (varPu)b = .137652D+00
The var of    Pu    (varPu)  = .137655D+00
The std of    Pu    (stdPu)  = .371019D+00
The cov of    Pu    (covPu)  = .301177D+02
The var of avePu (varAvePu)b = .275305D-05
The var of avePu (varAvePu)  = .275310D-05
The std of avePu (stdAvePu)  = .165925D-02
The cov of avePu (covAvePu)  = .134691D+00
b = biased, for variance computation using the sample size N.
```

Output of Importance Sampling - IS02 (SF_t =1.5)

```
Title =   Title ASM-1b01
Total number of random variables =   11

***** The input data *****

-x=rv- --name-- ----mean---- ---Sigma---- ----cov----- code Type
X(  1) STRU 0 1  .150000D+00  .225000D-01  .150000D+00    C  NOR
X(  2) SOLT 1 3  .280000D+02  .840000D+01  .300000D+00    C  NOR
X(  3) SOLT 1 5  .120000D+00  .120000D-01  .100000D+00    C  NOR
X(  4) SORT 1 3  .280000D+02  .840000D+01  .300000D+00    C  NOR
X(  5) SORT 1 5  .120000D+00  .120000D-01  .100000D+00    C  NOR
X(  6) SOST 0 3  .300000D+02  .900000D+01  .300000D+00    C  NOR
X(  7) WATR 0 1  .500000D+01  .100000D+01  .200000D+00    S  NOR
X(  8) WATR 0 2  .150000D+01  .100000D+01  .666667D+00    S  NOR
X(  9) VPLO 1 5  .200000D+01  .300000D+00  .150000D+00    C  LOG
X( 10) VSLO 1 5  .800000D+00  .120000D+00  .150000D+00    C  LOG
X( 11) VRLO 1 5  .550000D+00  .825000D-01  .150000D+00    C  LOG

The limit state Z=R-L=L(SF-1) or Z=SF-1

The simulation cycle    =        50000
The initial given  seed =     -4175144
The sensitivity test ratio         =  .100000D+00
The target safety factor           =  .150000D+01
The initial output cycle increment =            0

<<< The sensitivity result >>>

The safety factor (SF) =  .182545E+01

-x=rv- --Name-- --M=Mean-- SF1:M* .90 SF2:M*1.10 --SF1-SF- --SF2-SF-- --
Sense.--
X(  1) STRU 0 1  .1500D+00  .1796D+01  .1854D+01 -.2896D-01  .2886D-01
.9000D+00
X(  2) SOLT 1 3  .2800D+02  .1739D+01  .1915D+01 -.8680D-01  .8926D-01
.9000D+00
X(  3) SOLT 1 5  .1200D+00  .1878D+01  .1779D+01  .5298D-01 -.4615D-01
.1100D+01
X(  4) SORT 1 3  .2800D+02  .1782D+01  .1872D+01 -.4390D-01  .4684D-01
.9000D+00
X(  5) SORT 1 5  .1200D+00  .1798D+01  .1853D+01 -.2758D-01  .2781D-01
.9000D+00
X(  6) SOST 0 3  .3000D+02  .1743D+01  .1912D+01 -.8206D-01  .8633D-01
.9000D+00
X(  7) WATR 0 1  .5000D+01  .1837D+01  .1814D+01  .1117D-01 -.1126D-01
.1100D+01
X(  8) WATR 0 2  .1500D+01  .1831D+01  .1820D+01  .5501D-02 -.5618D-02
.1100D+01
X(  9) VPLO 1 5  .2000D+01  .1825D+01  .1825D+01  .0000D+00  .0000D+00
.1000D+01
X( 10) VSLO 1 5  .8000D+00  .1772D+01  .1880D+01 -.5366D-01  .5458D-01
.9000D+00
X( 11) VRLO 1 5  .5500D+00  .1876D+01  .1779D+01  .5020D-01 -.4611D-01
.1100D+01


<<< The shifted means >>>
-x=rv- --Name-- ---M=Mean--- Shifted.Mean ---Ratio----
X(  1) STRU 0 1  .150000D+00  .135000D+00  .900000D+00
X(  2) SOLT 1 3  .280000D+02  .252000D+02  .900000D+00
X(  3) SOLT 1 5  .120000D+00  .132000D+00  .110000D+01
X(  4) SORT 1 3  .280000D+02  .252000D+02  .900000D+00
X(  5) SORT 1 5  .120000D+00  .108000D+00  .900000D+00
X(  6) SOST 0 3  .300000D+02  .270000D+02  .900000D+00
X(  7) WATR 0 1  .500000D+01  .550000D+01  .110000D+01
X(  8) WATR 0 2  .150000D+01  .165000D+01  .110000D+01
X(  9) VPLO 1 5  .200000D+01  .200000D+01  .100000D+01
X( 10) VSLO 1 5  .800000D+00  .720000D+00  .900000D+00
X( 11) VRLO 1 5  .550000D+00  .605000D+00  .110000D+01
```

```
The safety factor =  .143618D+01
The iteration of shifting =    1

***** The result *****

The revised output cycle increment =          500

*** The result of importance sampling simulation ***

=========================
No.of.cycle- -ave.cum.Pu-
------------ ------------
         500  .114841E-01
        1000  .110619E-01
        1500  .115797E-01
        2000  .940005E-02
        2500  .882741E-02
        3000  .820059E-02
        3500  .888176E-02
        4000  .832656E-02
        4500  .826378E-02
        5000  .889562E-02
        5500  .968442E-02
        6000  .933157E-02
        6500  .934384E-02
        7000  .918440E-02
        7500  .903444E-02
        8000  .916210E-02
        8500  .911424E-02
        9000  .940873E-02
        9500  .958788E-02
       10000  .102034E-01
       10500  .102879E-01
       11000  .997049E-02
       11500  .101574E-01
       12000  .102058E-01
       12500  .996347E-02
       13000  .976166E-02
       13500  .988919E-02
       14000  .101289E-01
       14500  .100602E-01
       15000  .100594E-01
       15500  .994770E-02
       16000  .982323E-02
       16500  .966996E-02
       17000  .961503E-02
       17500  .973809E-02
       18000  .952750E-02
       18500  .948915E-02
       19000  .958080E-02
       19500  .953854E-02
       20000  .961472E-02
       20500  .955461E-02
       21000  .958697E-02
       21500  .945272E-02
       22000  .935398E-02
       22500  .924403E-02
       23000  .912753E-02
       23500  .935799E-02
       24000  .934265E-02
       24500  .933448E-02
       25000  .931839E-02
       25500  .942703E-02
       26000  .950188E-02
       26500  .943946E-02
       27000  .937886E-02
       27500  .925511E-02
       28000  .919671E-02
       28500  .921812E-02
       29000  .910797E-02
       29500  .924519E-02
       30000  .925946E-02
       30500  .932726E-02
```

```
       31000  .938460E-02
       31500  .988154E-02
       32000  .978469E-02
       32500  .975847E-02
       33000  .978069E-02
       33500  .979664E-02
       34000  .105081E-01
       34500  .104348E-01
       35000  .104052E-01
       35500  .104833E-01
       36000  .104445E-01
       36500  .103646E-01
       37000  .103946E-01
       37500  .103583E-01
       38000  .107490E-01
       38500  .106795E-01
       39000  .106835E-01
       39500  .106057E-01
       40000  .105313E-01
       40500  .104907E-01
       41000  .105045E-01
       41500  .105086E-01
       42000  .104417E-01
       42500  .105012E-01
       43000  .104821E-01
       43500  .104270E-01
       44000  .103719E-01
       44500  .104500E-01
       45000  .104161E-01
       45500  .104109E-01
       46000  .103741E-01
       46500  .103418E-01
       47000  .103337E-01
       47500  .103191E-01
       48000  .102739E-01
       48500  .102667E-01
       49000  .102907E-01
       49500  .103235E-01
       50000  .103543E-01
=========================

The importance failure count =        4005

The safety factor > 10 count =          31

The reliability index        = .231326D+01

The binomial statistics
The ave of    Pu    (AvePu)  = .103543D-01
The var of avePu (varAvePu)  = .204941D-06
The std of avePu (stdAvePu)  = .452704D-03
The cov of avePu (covAvePu)  = .437215D-01


The simulation and sample mean statistics
The ave of    Pu    (avePu)  = .103543D-01
The var of    Pu    (varPu)b = .295834D-01
The var of    Pu    (varPu)  = .295840D-01
The std of    Pu    (stdPu)  = .172000D+00
The cov of    Pu    (covPu)  = .166115D+02
The var of avePu (varAvePu)b = .591669D-06
The var of avePu (varAvePu)  = .591681D-06
The std of avePu (stdAvePu)  = .769208D-03
The cov of avePu (covAvePu)  = .742890D-01
b = biased, for variance computation using the sample size N.
```

Output of Direct Monte Carlo Simulation (MCS) - DR01 (SF_t =1.82545)

```
Title =   Title ASM-1b01
Total number of random variables =   11

***** The input data *****

-x=rv- --name-- ----mean---- ---Sigma---- ----cov----- code Type
X(  1) STRU 0 1  .150000D+00  .225000D-01  .150000D+00    C  NOR
X(  2) SOLT 1 3  .280000D+02  .840000D+01  .300000D+00    C  NOR
X(  3) SOLT 1 5  .120000D+00  .120000D-01  .100000D+00    C  NOR
X(  4) SORT 1 3  .280000D+02  .840000D+01  .300000D+00    C  NOR
X(  5) SORT 1 5  .120000D+00  .120000D-01  .100000D+00    C  NOR
X(  6) SOST 0 3  .300000D+02  .900000D+01  .300000D+00    C  NOR
X(  7) WATR 0 1  .500000D+01  .100000D+01  .200000D+00    S  NOR
X(  8) WATR 0 2  .150000D+01  .100000D+01  .666667D+00    S  NOR
X(  9) VPLO 1 5  .200000D+01  .300000D+00  .150000D+00    C  LOG
X( 10) VSLO 1 5  .800000D+00  .120000D+00  .150000D+00    C  LOG
X( 11) VRLO 1 5  .550000D+00  .825000D-01  .150000D+00    C  LOG

The limit state Z=R-L=L(SF-1) or Z=SF-1

The simulation cycle    =        50000
The initial given  seed =      -362646
The sensitivity test ratio         =  .100000D+00
The target safety factor           =  .100000D+00
The initial output cycle increment =            0

***** The result *****

The revised output cycle increment =          500

*** The result of direct simulation ***

=========================
No.of.cycle- -ave.cum.Pu-
------------ ------------
         500  .400000E-02
        1000  .130000E-01
        1500  .113333E-01
        2000  .100000E-01
        2500  .108000E-01
        3000  .103333E-01
        3500  .111429E-01
        4000  .107500E-01
        4500  .104444E-01
        5000  .102000E-01
        5500  .100000E-01
        6000  .100000E-01
        6500  .953846E-02
        7000  .101429E-01
        7500  .986667E-02
        8000  .100000E-01
        8500  .101176E-01
        9000  .101111E-01
        9500  .989474E-02
       10000  .980000E-02
       10500  .100952E-01
       11000  .100000E-01
       11500  .100870E-01
       12000  .101667E-01
       12500  .100800E-01
       13000  .992308E-02
       13500  .985185E-02
       14000  .992857E-02
       14500  .100000E-01
       15000  .100667E-01
       15500  .100645E-01
       16000  .101250E-01
       16500  .100000E-01
```

```
       17000  .100588E-01
       17500  .994286E-02
       18000  .988889E-02
       18500  .101622E-01
       19000  .100526E-01
       19500  .994872E-02
       20000  .995000E-02
       20500  .995122E-02
       21000  .995238E-02
       21500  .100000E-01
       22000  .995455E-02
       22500  .102667E-01
       23000  .101739E-01
       23500  .101702E-01
       24000  .102083E-01
       24500  .102041E-01
       25000  .102800E-01
       25500  .101176E-01
       26000  .101154E-01
       26500  .101509E-01
       27000  .101111E-01
       27500  .101091E-01
       28000  .996429E-02
       28500  .989474E-02
       29000  .982759E-02
       29500  .983051E-02
       30000  .986667E-02
       30500  .996721E-02
       31000  .987097E-02
       31500  .971429E-02
       32000  .971875E-02
       32500  .969231E-02
       33000  .963636E-02
       33500  .958209E-02
       34000  .955882E-02
       34500  .959420E-02
       35000  .948571E-02
       35500  .949296E-02
       36000  .955556E-02
       36500  .950685E-02
       37000  .951351E-02
       37500  .952000E-02
       38000  .963158E-02
       38500  .961039E-02
       39000  .958974E-02
       39500  .954430E-02
       40000  .955000E-02
       40500  .958025E-02
       41000  .953659E-02
       41500  .949398E-02
       42000  .961905E-02
       42500  .969412E-02
       43000  .965116E-02
       43500  .967816E-02
       44000  .965909E-02
       44500  .966292E-02
       45000  .966667E-02
       45500  .971429E-02
       46000  .967391E-02
       46500  .965591E-02
       47000  .965957E-02
       47500  .972632E-02
       48000  .970833E-02
       48500  .967010E-02
       49000  .963265E-02
       49500  .959596E-02
       50000  .960000E-02
=========================

The importance failure count =         480

The safety factor > 10 count =           9
```

```
The reliability index        = .234162D+01

The binomial statistics
The ave of    Pu    (AvePu)  = .960000D-02
The var of avePu (varAvePu)  = .190157D-06
The std of avePu (stdAvePu)  = .436070D-03
The cov of avePu (covAvePu)  = .454239D-01
```

Output of Direct Monte Carlo Simulation (MCS) - DR02 (SF_t =1.82545)

```
Title =   Title ASM-1b01
Total number of random variables =   11

***** The input data *****

-x=rv- --name-- ----mean---- ---Sigma---- ----cov----- code Type
X(  1) STRU 0 1  .150000D+00  .225000D-01  .150000D+00    C  NOR
X(  2) SOLT 1 3  .280000D+02  .840000D+01  .300000D+00    C  NOR
X(  3) SOLT 1 5  .120000D+00  .120000D-01  .100000D+00    C  NOR
X(  4) SORT 1 3  .280000D+02  .840000D+01  .300000D+00    C  NOR
X(  5) SORT 1 5  .120000D+00  .120000D-01  .100000D+00    C  NOR
X(  6) SOST 0 3  .300000D+02  .900000D+01  .300000D+00    C  NOR
X(  7) WATR 0 1  .500000D+01  .100000D+01  .200000D+00    S  NOR
X(  8) WATR 0 2  .150000D+01  .100000D+01  .666667D+00    S  NOR
X(  9) VPLO 1 5  .200000D+01  .300000D+00  .150000D+00    C  LOG
X( 10) VSLO 1 5  .800000D+00  .120000D+00  .150000D+00    C  LOG
X( 11) VRLO 1 5  .550000D+00  .825000D-01  .150000D+00    C  LOG

The limit state Z=R-L=L(SF-1) or Z=SF-1

The simulation cycle    =        50000
The initial given  seed =     -4175144
The sensitivity test ratio         =  .100000D+00
The target safety factor           =  .100000D+00
The initial output cycle increment =            0

***** The result *****

The revised output cycle increment =          500

*** The result of direct simulation ***

=========================
No.of.cycle- -ave.cum.Pu-
------------ ------------
         500  .800000E-02
        1000  .130000E-01
        1500  .100000E-01
        2000  .950000E-02
        2500  .104000E-01
        3000  .966667E-02
        3500  .971429E-02
        4000  .112500E-01
        4500  .108889E-01
        5000  .108000E-01
        5500  .107273E-01
        6000  .110000E-01
        6500  .107692E-01
        7000  .111429E-01
        7500  .113333E-01
        8000  .111250E-01
        8500  .107059E-01
        9000  .108889E-01
        9500  .105263E-01
       10000  .108000E-01
       10500  .109524E-01
       11000  .106364E-01
       11500  .106087E-01
       12000  .105833E-01
       12500  .103200E-01
       13000  .103077E-01
       13500  .102963E-01
       14000  .102857E-01
       14500  .103448E-01
       15000  .104667E-01
       15500  .105161E-01
       16000  .104375E-01
       16500  .106061E-01
```

```
        17000  .105882E-01
        17500  .107429E-01
        18000  .106111E-01
        18500  .105946E-01
        19000  .107895E-01
        19500  .107692E-01
        20000  .107500E-01
        20500  .107317E-01
        21000  .105714E-01
        21500  .105581E-01
        22000  .107273E-01
        22500  .107111E-01
        23000  .106087E-01
        23500  .105957E-01
        24000  .105833E-01
        24500  .106122E-01
        25000  .106800E-01
        25500  .106275E-01
        26000  .106923E-01
        26500  .105660E-01
        27000  .106667E-01
        27500  .105455E-01
        28000  .105357E-01
        28500  .104912E-01
        29000  .104483E-01
        29500  .103729E-01
        30000  .103667E-01
        30500  .104590E-01
        31000  .104516E-01
        31500  .103492E-01
        32000  .102500E-01
        32500  .102154E-01
        33000  .101818E-01
        33500  .100597E-01
        34000  .100000E-01
        34500  .100580E-01
        35000  .994286E-02
        35500  .991549E-02
        36000  .986111E-02
        36500  .980822E-02
        37000  .978378E-02
        37500  .973333E-02
        38000  .971053E-02
        38500  .971429E-02
        39000  .966667E-02
        39500  .969620E-02
        40000  .975000E-02
        40500  .975309E-02
        41000  .970732E-02
        41500  .973494E-02
        42000  .976190E-02
        42500  .981176E-02
        43000  .981395E-02
        43500  .981609E-02
        44000  .977273E-02
        44500  .979775E-02
        45000  .100222E-01
        45500  .100440E-01
        46000  .997826E-02
        46500  .993548E-02
        47000  .991489E-02
        47500  .989474E-02
        48000  .987500E-02
        48500  .987629E-02
        49000  .989796E-02
        49500  .989899E-02
        50000  .100000E-01
=========================

The importance failure count =         500

The safety factor > 10 count =           9
```

```
The reliability index        = .232635D+01

The binomial statistics
The ave of    Pu    (AvePu)  = .100000D-01
The var of avePu (varAvePu)  = .198000D-06
The std of avePu (stdAvePu)  = .444972D-03
The cov of avePu (covAvePu)  = .444972D-01
```

Appendix B
Input and Output Data for Case Study 2 (Correlation)

Input Data for CSLIDE

```
001 TITL RETAINING WALL with correlation
002 TITL
003 TITL
004 TITL
005 STRU  8  1.500000E-01  0.000000E+00  1.000000E+00
006     0.00     0.00
007     0.00     2.00
008     6.00     2.00
009     6.00    14.00
010     8.00    14.00
011     8.00     2.00
012    12.00     2.00
013    12.00     0.00
014 SOLT  1  1  .280000E+02  .500000E-01  .120000E+00  .140000E+02
015  -500.00    14.00
016 SORT  1  1  .280000E+02  .500000E-01  .120000E+00  .400000E+01
017   500.00     4.00
018 SOST  3.000000E+01  0.500000E-01
019 METH  1
020 WATR  5.000000E+00  1.500000E+00  6.250000E-02  -1
021 END
```

Input Data for Reliability Methods

```
TITL  ASM/MCS data file for X0075d1e.dat - correlation
STRU0001  1.500000E-01  1.500000E-01 C NOR
SOLT0103  2.800000E+01  3.000000E-01 C NOR
SOLT0104  5.000000E-02  2.000000E-01 C LOG -0.5
SOLT0105  1.200000E-01  1.000000E-01 C NOR
SORT0103  2.800000E+01  3.000000E-01 C NOR
SORT0104  5.000000E-02  2.000000E-01 C LOG -0.5
SORT0105  1.200000E-01  1.000000E-01 C NOR
SOST0003  3.000000E+01  3.000000E-01 C NOR
SOST0004  5.000000E-02  1.000000E-02 C NOR -0.5
WATR0001  5.000000E+00  1.000000E+00 S NOR
WATR0002  1.000000E+00  1.000000E+00 S NOR
END
```

Output of Advanced Second Moment (ASM) Method

```
Title =   ASM/MCS data file for X0075d1e.dat - correlation
Total number of random variables =   11

***** The input data *****
-x=rv- --name-- ----mean---- ---Sigma---- ----cov----- code Type
X(  1) STRU 0 1  .150000D+00  .225000D-01  .150000D+00    C  NOR
X(  2) SOLT 1 3  .280000D+02  .840000D+01  .300000D+00    C  NOR
X(  3) SOLT 1 4  .500000D-01  .100000D-01  .200000D+00    C  NOR
Correlation for SOLT 1 =  -.500000D+00
X(  4) SOLT 1 5  .120000D+00  .120000D-01  .100000D+00    C  NOR
X(  5) SORT 1 3  .280000D+02  .840000D+01  .300000D+00    C  NOR
X(  6) SORT 1 4  .500000D-01  .100000D-01  .200000D+00    C  NOR
Correlation for SORT 1 =  -.500000D+00
X(  7) SORT 1 5  .120000D+00  .120000D-01  .100000D+00    C  NOR
X(  8) SOST 0 3  .300000D+02  .900000D+01  .300000D+00    C  NOR
X(  9) SOST 0 4  .500000D-01  .500000D-03  .100000D-01    C  NOR
Correlation for SOST 0 =  -.500000D+00
X( 10) WATR 0 1  .500000D+01  .100000D+01  .200000D+00    S  NOR
X( 11) WATR 0 2  .100000D+01  .100000D+01  .100000D+01    S  NOR

The tolerance of reliability index (beta)    = .100000D-01
The ratio of dx/x for random variables       = .100000D-02
The max. iterations for finding beta         = 10
The increment for finding beta               =   .2500
The 1=absolute 2=relative tolerance for beta =  2

The limit state Z=R-L=L(SF-1) or Z=SF-1

***** The result *****
The iteration No. = 1
-i ---meanEN--- ----stdEN--- ---alpha---- -----dp----- -Partial.SF-
 1  .150000D+00  .225000D-01  .156951D+00  .140263D+00  .935089D+00
 2  .280000D+02  .840000D+01  .309218D+00  .155451D+02  .555182D+00
 3  .500000D-01  .100000D-01  .442436D+00  .563016D-01  .112603D+01
 4  .120000D+00  .120000D-01 -.206591D+00  .126835D+00  .105696D+01
 5  .280000D+02  .840000D+01  .881481D-01  .248299D+02  .886783D+00
 6  .500000D-01  .100000D-01  .107158D+00  .513435D-01  .102687D+01
 7  .120000D+00  .120000D-01  .944139D-01  .116876D+00  .973968D+00
 8  .300000D+02  .900000D+01  .386014D+00  .108986D+02  .363286D+00
 9  .500000D-01  .500000D-03  .665983D+00  .505290D-01  .101058D+01
10  .500000D+01  .100000D+01 -.817605D-01  .522543D+01  .104509D+01
11  .100000D+01  .100000D+01 -.118017D+00  .132539D+01  .132539D+01
The reliability index (beta) =  .275718D+01

The iteration No. = 2
-i ---meanEN--- ----stdEN--- ---alpha---- -----dp----- -Partial.SF-
 1  .150000D+00  .225000D-01  .732600D-01  .145438D+00  .969584D+00
 2  .280000D+02  .840000D+01  .298147D+00  .150548D+02  .537673D+00
 3  .500000D-01  .100000D-01  .470781D+00  .571586D-01  .114317D+01
 4  .120000D+00  .120000D-01 -.202887D+00  .126739D+00  .105616D+01
 5  .280000D+02  .840000D+01  .167632D+00  .202051D+02  .721612D+00
 6  .500000D-01  .100000D-01  .290346D+00  .546398D-01  .109280D+01
 7  .120000D+00  .120000D-01  .768691D-01  .117447D+00  .978724D+00
 8  .300000D+02  .900000D+01  .362025D+00  .119634D+02  .398781D+00
 9  .500000D-01  .500000D-03  .627046D+00  .505010D-01  .101002D+01
10  .500000D+01  .100000D+01 -.196054D-01  .505426D+01  .101085D+01
11  .100000D+01  .100000D+01  .000000D+00  .100000D+01  .100000D+01

The reliability index (beta) =  .276785D+01
The unsatisfactory performance probability =  .282136D-02
```

Output of Advanced Second Moment (ASM) Method (Without Correlation)

```
Title =   ASM/MCS data file for X0075d1d.dat - Without correlation
Total number of random variables =   11

***** The input data *****
-x=rv- --name-- ----mean---- ---Sigma---- ----cov----- code Type
X(  1) STRU 0 1  .150000D+00  .225000D-01  .150000D+00    C  NOR
X(  2) SOLT 1 3  .280000D+02  .840000D+01  .300000D+00    C  NOR
X(  3) SOLT 1 4  .500000D-01  .100000D-01  .200000D+00    C  NOR
X(  4) SOLT 1 5  .120000D+00  .120000D-01  .100000D+00    C  NOR
X(  5) SORT 1 3  .280000D+02  .840000D+01  .300000D+00    C  NOR
X(  6) SORT 1 4  .500000D-01  .100000D-01  .200000D+00    C  NOR
X(  7) SORT 1 5  .120000D+00  .120000D-01  .100000D+00    C  NOR
X(  8) SOST 0 3  .300000D+02  .900000D+01  .300000D+00    C  NOR
X(  9) SOST 0 4  .500000D-01  .500000D-03  .100000D-01    C  NOR
X( 10) WATR 0 1  .500000D+01  .100000D+01  .200000D+00    S  NOR
X( 11) WATR 0 2  .100000D+01  .100000D+01  .100000D+01    S  NOR

The tolerance of reliability index (beta)    = .100000D-01
The ratio of dx/x for random variables       = .100000D-02
The max. iterations for finding beta         = 10
The increment for finding beta               =   .2500
The 1=absolute 2=relative tolerance for beta =  2

The limit state Z=R-L=L(SF-1) or Z=SF-1

***** The result *****
The iteration No. = 1
-i ---meanEN--- ----stdEN--- ---alpha---- -----dp----- -Partial.SF-
 1  .150000D+00  .225000D-01  .154239D+00  .140666D+00  .937776D+00
 2  .280000D+02  .840000D+01  .554903D+00  .154637D+02  .552275D+00
 3  .500000D-01  .100000D-01  .528479D-01  .485787D-01  .971573D+00
 4  .120000D+00  .120000D-01 -.203022D+00  .126552D+00  .105460D+01
 5  .280000D+02  .840000D+01  .147424D+00  .246694D+02  .881050D+00
 6  .500000D-01  .100000D-01  .258261D-01  .493054D-01  .986108D+00
 7  .120000D+00  .120000D-01  .927828D-01  .117006D+00  .975046D+00
 8  .300000D+02  .900000D+01  .757208D+00  .116713D+02  .389045D+00
 9  .500000D-01  .500000D-03  .148261D-02  .499980D-01  .999960D+00
10  .500000D+01  .100000D+01 -.803480D-01  .521610D+01  .104322D+01
11  .100000D+01  .100000D+01 -.115978D+00  .131193D+01  .131193D+01
The reliability index (beta) =  .268951D+01

The iteration No. = 2
-i ---meanEN--- ----stdEN--- ---alpha---- -----dp----- -Partial.SF-
 1  .150000D+00  .225000D-01  .501094D-01  .146978D+00  .979856D+00
 2  .280000D+02  .840000D+01  .644404D+00  .134931D+02  .481895D+00
 3  .500000D-01  .100000D-01  .364587D-01  .490229D-01  .980458D+00
 4  .120000D+00  .120000D-01 -.167458D+00  .125385D+00  .104488D+01
 5  .280000D+02  .840000D+01  .283456D+00  .216188D+02  .772100D+00
 6  .500000D-01  .100000D-01  .279344D-01  .492514D-01  .985027D+00
 7  .120000D+00  .120000D-01  .924095D-01  .117028D+00  .975234D+00
 8  .300000D+02  .900000D+01  .674410D+00  .137331D+02  .457770D+00
 9  .500000D-01  .500000D-03  .136366D-02  .499982D-01  .999963D+00
10  .500000D+01  .100000D+01 -.288841D-01  .507741D+01  .101548D+01
11  .100000D+01  .100000D+01 -.867651D-01  .123253D+01  .123253D+01

The reliability index (beta) =  .268002D+01
The unsatisfactory performance probability =  .368090D-02
```

Output of Direct Monte Carlo Simulation

```
Title =   ASM/MCS data file for X0075d1e.dat - correlation
Total number of random variables =   11

***** The input data *****
-x=rv- --name-- ----mean---- ---Sigma---- ----cov----- code Type
X(  1) STRU 0 1  .150000D+00  .225000D-01  .150000D+00    C  NOR
X(  2) SOLT 1 3  .280000D+02  .840000D+01  .300000D+00    C  NOR
X(  3) SOLT 1 4  .500000D-01  .100000D-01  .200000D+00    C  NOR
Correlation for SOLT 1 =  -.500000D+00
X(  4) SOLT 1 5  .120000D+00  .120000D-01  .100000D+00    C  NOR
X(  5) SORT 1 3  .280000D+02  .840000D+01  .300000D+00    C  NOR
X(  6) SORT 1 4  .500000D-01  .100000D-01  .200000D+00    C  NOR
Correlation for SORT 1 =  -.500000D+00
X(  7) SORT 1 5  .120000D+00  .120000D-01  .100000D+00    C  NOR
X(  8) SOST 0 3  .300000D+02  .900000D+01  .300000D+00    C  NOR
X(  9) SOST 0 4  .500000D-01  .500000D-03  .100000D-01    C  NOR
Correlation for SOST 0 =  -.500000D+00
X( 10) WATR 0 1  .500000D+01  .100000D+01  .200000D+00    S  NOR
X( 11) WATR 0 2  .100000D+01  .100000D+01  .100000D+01    S  NOR

The limit state Z=R-L=L(SF-1) or Z=SF-1
 The simulation cycle    =        3000
 The initial given  seed =           0
 The simulation output increment    =          10
 The target safety factor           =  .180000D+01
 The safety factor shift ratio      =  .100000D+00

The safety factor (SF)       = .193198E+01

***** The result *****
 The initial random seed =     -1142561
*** The result of direct simulation ***
===================================================
No.of.cycle- -ave.cum.Pf- -COV(avePf)- B.COV(avePf)
------------ ------------ ------------ ------------
          10  .000000E+00
          20  .000000E+00
          30  .333333E-01  .000000E+00  .983192E+00
          40  .250000E-01  .000000E+00  .987421E+00
          50  .200000E-01  .000000E+00  .989949E+00
          60  .166667E-01  .000000E+00  .991632E+00
          70  .142857E-01  .000000E+00  .992831E+00
          80  .125000E-01  .000000E+00  .993730E+00
          90  .111111E-01  .000000E+00  .994429E+00
         100  .100000E-01  .000000E+00  .994987E+00
         500  .600000E-02  .000000E+00  .575616E+00
        1000  .700000E-02  .000000E+00  .376639E+00
        1500  .733333E-02  .000000E+00  .300404E+00
        2000  .600000E-02  .000000E+00  .287808E+00
        2500  .560000E-02  .000000E+00  .266512E+00
        2900  .517241E-02  .000000E+00  .257530E+00
        2910  .515464E-02  .000000E+00  .257533E+00
        2920  .513699E-02  .000000E+00  .257535E+00
        2930  .511945E-02  .000000E+00  .257537E+00
        2940  .510204E-02  .000000E+00  .257539E+00
        2950  .508475E-02  .000000E+00  .257542E+00
        2960  .506757E-02  .000000E+00  .257544E+00
        2970  .505051E-02  .000000E+00  .257546E+00
        2980  .503356E-02  .000000E+00  .257548E+00
        2990  .501672E-02  .000000E+00  .257550E+00
        3000  .500000E-02  .000000E+00  .257553E+00
===================================================
The importance failure count =         15
The safety factor > 10 count =          0
The reliability index (beta) = .257583E+01
The binomial statistics
The ave of    Pf    (AvePf)  = .500000D-02
The var of avePf (varAvePf)  = .165833D-05
The std of avePf (stdAvePf)  = .128776D-02
The cov of avePf (covAvePf)  = .257553D+00
```

Output of Importance Sampling (SF_t =1.8)

```
Title =   ASM/MCS data file for X0075d1e.dat - correlation
Total number of random variables =   11

***** The input data *****
-x=rv- --name-- ----mean---- ---Sigma---- ----cov----- code Type
X(  1) STRU 0 1  .150000D+00  .225000D-01  .150000D+00    C  NOR
X(  2) SOLT 1 3  .280000D+02  .840000D+01  .300000D+00    C  NOR
X(  3) SOLT 1 4  .500000D-01  .100000D-01  .200000D+00    C  NOR
Correlation for SOLT 1 =  -.500000D+00
X(  4) SOLT 1 5  .120000D+00  .120000D-01  .100000D+00    C  NOR
X(  5) SORT 1 3  .280000D+02  .840000D+01  .300000D+00    C  NOR
X(  6) SORT 1 4  .500000D-01  .100000D-01  .200000D+00    C  NOR
Correlation for SORT 1 =  -.500000D+00
X(  7) SORT 1 5  .120000D+00  .120000D-01  .100000D+00    C  NOR
X(  8) SOST 0 3  .300000D+02  .900000D+01  .300000D+00    C  NOR
X(  9) SOST 0 4  .500000D-01  .500000D-03  .100000D-01    C  NOR
Correlation for SOST 0 =  -.500000D+00
X( 10) WATR 0 1  .500000D+01  .100000D+01  .200000D+00    S  NOR
X( 11) WATR 0 2  .100000D+01  .100000D+01  .100000D+01    S  NOR

The limit state Z=R-L=L(SF-1) or Z=SF-1
The simulation cycle    =         3000
The initial given  seed =            0
The simulation output increment    =           10
The target safety factor           =  .180000D+01
The safety factor shift ratio      =  .100000D+00

<<< The sensitivity result >>>
The safety factor (SF)       = .193198E+01
-x=rv- --Name-- --M=Mean-- SF1:M* .90 SF2:M*1.10 --SF1-SF- --SF2-SF-- --
Sense.--
X(  1) STRU 0 1  .1500D+00  .1889D+01  .1975D+01 -.4312D-01  .4293D-01
.9000D+00
X(  2) SOLT 1 3  .2800D+02  .1855D+01  .2010D+01 -.7651D-01  .7842D-01
.9000D+00
X(  3) SOLT 1 4  .5000D-01  .1921D+01  .1943D+01 -.1103D-01  .1105D-01
.9000D+00
X(  4) SOLT 1 5  .1200D+00  .2027D+01  .1855D+01  .9475D-01 -.7692D-01
.1100D+01
X(  5) SORT 1 3  .2800D+02  .1912D+01  .1954D+01 -.1969D-01  .2156D-01
.9000D+00
X(  6) SORT 1 4  .5000D-01  .1927D+01  .1937D+01 -.5437D-02  .5427D-02
.9000D+00
X(  7) SORT 1 5  .1200D+00  .1893D+01  .1971D+01 -.3856D-01  .3903D-01
.9000D+00
X(  8) SOST 0 3  .3000D+02  .1829D+01  .2040D+01 -.1031D+00  .1084D+00
.9000D+00
X(  9) SOST 0 4  .5000D-01  .1926D+01  .1938D+01 -.6211D-02  .6208D-02
.9000D+00
X( 10) WATR 0 1  .5000D+01  .1949D+01  .1915D+01  .1670D-01 -.1684D-01
.1100D+01
X( 11) WATR 0 2  .1000D+01  .1962D+01  .1952D+01  .2978D-01  .2008D-01
.1100D+01

<<< The shifted means >>>
**NOTE** correlated random variables were not shifted**
-x=rv- --Name-- ---M=Mean--- Shifted.Mean ---Ratio----
X(  1) STRU 0 1  .150000D+00  .135000D+00  .900000D+00
X(  2) SOLT 1 3  .280000D+02  .280000D+02  .100000D+01
X(  3) SOLT 1 4  .500000D-01  .500000D-01  .100000D+01
X(  4) SOLT 1 5  .120000D+00  .132000D+00  .110000D+01
X(  5) SORT 1 3  .280000D+02  .280000D+02  .100000D+01
X(  6) SORT 1 4  .500000D-01  .500000D-01  .100000D+01
X(  7) SORT 1 5  .120000D+00  .108000D+00  .900000D+00
X(  8) SOST 0 3  .300000D+02  .300000D+02  .100000D+01
X(  9) SOST 0 4  .500000D-01  .500000D-01  .100000D+01
X( 10) WATR 0 1  .500000D+01  .550000D+01  .110000D+01
X( 11) WATR 0 2  .100000D+01  .110000D+01  .110000D+01
The safety factor =  .158121D+01
The iteration of shifting =    1
```

```
***** The result *****
The initial random seed =     -9527654
*** The result of importance sampling simulation ***
===================================================
No.of.cycle- -ave.cum.Pf- -COV(avePf)- B.COV(avePf)
------------ ------------ ------------ ------------
          10  .000000E+00
          20  .000000E+00
          30  .000000E+00
          40  .300743E-03  .698519E+00  .911605E+01
          50  .240595E-03  .700387E+00  .911633E+01
          60  .200495E-03  .701619E+00  .911651E+01
          70  .171853E-03  .702492E+00  .911664E+01
          80  .150372E-03  .703144E+00  .911674E+01
          90  .133664E-03  .703649E+00  .911681E+01
         100  .120297E-03  .704051E+00  .911687E+01
         500  .333459E-02  .991259E+00  .773159E+00
        1000  .199691E-02  .835725E+00  .706946E+00
        1500  .207756E-02  .594589E+00  .565882E+00
        2000  .355221E-02  .495030E+00  .374509E+00
        2500  .296705E-02  .475451E+00  .366625E+00
        2900  .292495E-02  .423550E+00  .342851E+00
        2910  .293193E-02  .421126E+00  .341853E+00
        2920  .292189E-02  .421127E+00  .341855E+00
        2930  .291191E-02  .421128E+00  .341856E+00
        2940  .290201E-02  .421129E+00  .341858E+00
        2950  .289217E-02  .421130E+00  .341860E+00
        2960  .288240E-02  .421131E+00  .341861E+00
        2970  .289210E-02  .418355E+00  .340711E+00
        2980  .288240E-02  .418356E+00  .340712E+00
        2990  .287276E-02  .418357E+00  .340714E+00
        3000  .286318E-02  .418358E+00  .340716E+00
===================================================
The importance failure count =          33
The safety factor > 10 count =           0
The reliability index (beta) = .276305E+01

The binomial statistics
The ave of    Pf    (AvePf)  = .286318D-02
The var of avePf (varAvePf)  = .951662D-06
The std of avePf (stdAvePf)  = .975532D-03
The cov of avePf (covAvePf)  = .340716D+00

The simulation and sample mean statistics
The ave of    Pf    (avePf)  = .286318D-02
The var of    Pf    (varPf)b = .430300D-02
The var of    Pf    (varPf)  = .430443D-02
The std of    Pf    (stdPf)  = .656082D-01
The cov of    Pf    (covPf)  = .229144D+02
The var of avePf (varAvePf)b = .143433D-05
The var of avePf (varAvePf)  = .143481D-05
The std of avePf (stdAvePf)  = .119784D-02
The cov of avePf (covAvePf)  = .418358D+00
b = biased, for variance computation using the sample size N
```

Appendix C
Notation

a	Value of a variable *X*
ASM	Advanced second moment (method)
b	Value of a variable *X* or regression coefficient
b_0	Intercept of a regression line between X_1 and X_2
b_1	Slope of the regression line
c	Value of a variable *X*
CDF	Cumulative distribution function
COV	Coefficient of variation
Cov	Covariance
CSLIDE	Software for stability assessment of concrete gravity structures
d	Total derivative
DIFF	Difference
DR	Direct simulation
dx	Differential of *x*
f	Probability density function
F	Cumulative distribution function or force
FOSM	First-order second moment method
G	Performance function
h	Importance density function
I	Performance indicator
INV	Inverse of cumulative distribution function
IS	Importance sampling
L	Load or length
LRFD	Load and resistance factor design
MCS	Monte Carlo simulation
MOM	Moments (mean and standard deviation)
N	Number of simulation cycles
P	Probability
PAR	Parameters
PDF	Probability density function
R	Strength or resistance
RCSLIDE	Software for reliability and stability assessment of concrete gravity structures
SF	Safety factor

Stddv	Standard deviation
t	$\sqrt{0.5}$
Var	Variance
X	Random variable
Y	Random variable
Z	Performance function
α	Directional cosine
β	Reliability index
Δ	Very small quantity
ε	Standard error for regression
γ	Partial safety factor
δ	Tolerance
Φ	Cumulative distribution function of standard normal variate
ϕ	Probability density function of standard normal variate
λ	Eigenvalue
μ	Mean
σ	Standard deviation
ρ	Correlation coefficient
∂	Partial derivative

<u>Subscripts</u>

i	i^{th} iteration (or component)
m	Mean
s	Shifted
t	Target
u	Unsatisfactory performance
X	Random variable

<u>Superscript</u>

N	Equivalent normal distribution
*	Design point
-1	Inverse of a function

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13. ABSTRACT (*Maximum 200 words*)

The reliability analysis of retaining walls and concrete gravity structures can be based on existing U.S. Army Corps of Engineers Computer-Aided Structural Engineering (CASE) performance assessment computer programs and algorithms for walls and structures that were validated over many years of use. The programs can be used to define the performance functions for reliability assessment. The objective of this study is to develop a reliability assessment methodology of the stability of concrete retaining walls and gravity structures based on an existing CASE computer program for evaluating their performance. The performance function for reliability assessment was defined in accordance with the CASE computer program. The reliability assessment methods used in this study include the advanced second moment method (ASM) and Monte Carlo Simulation (MCS) using importance sampling (IS). Correlated and noncorrelated random variables can be handled by the program. The computational procedure was developed around the CASE program for Sliding Stability of Concrete Structures (CSLIDE). Also, a user interface for CSLIDE and the reliability program based on CSLIDE (called RCSLIDE) was developed using Microsoft Visual BASIC. The software development procedure in this study is significant because it establishes a prototype reliability software that is modular and based on an existing CASE program.

14. SUBJECT TERMS

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Correlated random variables	Performance function	Sliding stability
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Instruction Report ITL-90-1	User's Guide: Computer Program for Design and Analysis of Sheet Pile Walls by Classical Methods (CWALSHT)	Feb 1990
Technical Report ITL-90-3	Investigation and Design of U-Frame Structures Using Program CUFRBC Volume A: Program Criteria and Documentation Volume B: User's Guide for Basins Volume C: User's Guide for Channels	May 1990
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