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Calibration of Safety Factors for Seismic Stability of Foundation Ground and Peripheral Slopes at Nuclear Power Sites

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Abstract

This paper investigates, within a probabilistic framework, the safety evaluation standard values for sliding failure safety factors (resistance/driving force) contained in the Japan Electric Association's "Technical Guidelines for Aseismic Design of Nuclear Power Plants", JEAG4601-1987. A survey of power plant operators was conducted and it was determined that standard values currently used for foundation ground and peripheral slopes at nuclear power sites are based on non-probabilistic criteria such as engineering judgment and accumulated knowledge. We then analyzed the efficacy of the standard values when applied to various analysis methods (dynamic, static, conventional) as well as to actual foundation ground and peripheral slope data. Our calibration study shows that the standard values specified in JEAG4601-1987 can be well substantiated in probabilistic terms, and that foundation ground and peripheral slopes which satisfy the standard values show sufficient levels of safety.

1. Introduction

The Nuclear and Safety Agency released their revised "Regulatory Guide for Aseismic Design of Nuclear Power Plants" on September 19, 2006. The revision was based on discussions held by the Japan atomic energy commission since 2001. The Japan Electric Association has revised their technical guideline to correspond to the revised government guide. Of particular interest to the risk community is the regulatory guide's explicit inclusion of residual risk resulting from earthquake ground motion exceeding the design one level. However, the guide fails to specify the evaluation method used for seismic PSA. Although residual risk is only used as a reference, its inclusion is a valuable step for future revisions. Civil engineers are also interested in standards for the stability of peripheral slopes and safety against tsunami and they should therefore evaluate the safety of peripheral slopes in addition to that of foundation ground. The factors used for the safety evaluation do not indicate safety conditions of the structure. Since the safety factors were determined based mainly on the level of satisfaction expressed by engineering experts, calibration of safety factors plays an important role in measuring the reliability of current design codes and in determining the direction of future codes.

This paper focuses on foundation ground and peripheral slopes for nuclear reactor buildings. The foundation ground is classified as the indirect support structure and commands the same level of importance as the supported structure. Both are categorized as Class As (superlative class) for seismic importance. Peripheral slopes are defined as slopes where the distance between the tail and the reactor building is less than 50 m or shorter than 1.4 times the slope height. Secondary effects on the function of buildings and equipment should also be avoided so that slope failure does not directly result in failure within the reactor building.

This paper presents the procedures for calibrating the safety evaluation standard values and the subsequent results. The reliability levels of foundation ground and peripheral slopes are estimated based on the standard values.

2. Summary of safety evaluation of foundation ground and peripheral slopes for nuclear buildings

This chapter summarizes the safety evaluation of foundation ground and peripheral slopes. The flowchart for the safety evaluation is shown in Figure 1. Basically, investigation is performed in the sequence of analyses using the sliding-plane method, static analysis, and dynamic analysis. Although JEAG4601-1991(Supplement) specifies that, in principle, all three analyses should be performed whether or not the prescribed safety standard values are satisfied, there is usually no need to perform analysis with higher precision when the specified safety standard values are satisfied in each analysis stage.

Safety evaluation standard values are specified in accordance with factors including the importance and type of structures. Both foundation ground and peripheral slopes should perform well in safety evaluations against a basic ground motion of S_2. While the safety evaluation procedures for both correspond to Class As, the aseismic importance is somewhat different. Foundation ground, which supports the nuclear reactor buildings including Class As structures, has been treated as indirect an support structure. On the other hand, because peripheral slopes do not contain radioactive substances directly support facilities containing radioactive substances, their evaluation is necessary only to confirm that their collapse would not have a secondary effect on the nuclear reactor building. Foundation ground is obviously of greater importance than peripheral slopes and therefore, requires higher standard values than those for peripheral slopes.

Safety evaluation standard values are dependent on the type of structure and analysis method used for evaluation. The standard values used in the JEAG4601-1987 are listed in Table 1. The same values are assigned for the sliding-plane method and the static analysis because both methods are believed to have the same analytic precision. Also, the standard values for foundation ground are also greater than those for peripheral slopes. The foundation ground is classified as an indirect support structure for the nuclear reactor building while the peripheral slopes are considered to have only a secondary influence on the nuclear reactor building. The standard values reflect the lower priority assigned to the effects of the collapse of peripheral slopes.

Safety evaluations of the foundation ground and peripheral slopes are performed using the sliding failure safety factor given as follows:

$$F_S = \frac{Sum\ of\ shear\ resistance\ forces\ on\ the\ sliding\ plane}{Sum\ of\ shear\ forces\ on\ the\ sliding\ plane} \quad (1)$$

It is necessary to verify that the factor obtained in the above equation is smaller than the standard value. When considering the seismic force used for the sliding-plane method, the horizontal seismic coefficient (K_H) is determined by the following equation.

$$K_H = n_1 \cdot n_2 \cdot K_o \quad (2)$$

where, n_1 and n_2 are correction coefficients for the site and magnification factor, respectively. The vertical seismic coefficient (K_V) is 1/2 of K_H. The coefficient n_2 is omitted from the equation for foundation ground. K_H=0.2 and K_V=0.1 can be applied for bedrock with an S-wave velocity of more than 500 m/s and a maximum acceleration of standard seismic motion (S_2) of less than 500 GAL. Also, K_H=0.3 and K_V=0.15 can be applied for peripheral slopes with an S-wave velocity of more than 300 m/s and a maximum acceleration of standard seismic motion (S_2) of less than 500 GAL. However, the applicability for over 500 GAL and the outside range is specified in JEAG4601-1987.

In the static analysis, factors such as stress distribution and displacement distribution were calculated by various methods including the finite-element method. Ground stress due to its own weight and seismic force are combined. The mode superposing method, direct integration method and complex value analysis method can be applied as the dynamic analysis for the evaluation of stress and displacement distributions. With the dynamic analysis their dynamic properties are used for calculations.

3. Calibration

3.1. Method of calibration

In the JEAG, the standard values for safety evaluations are smaller in the dynamic analysis than in the sliding-plane method and static analysis. However, the order of magnitude of the sliding failure safety factor for most analysis models is usually dynamic analysis, static analysis, and the sliding-plane method. We assume that this disagreement derives from the uncertainty of the analysis method. This is because the dynamic analysis contains only aleatory uncertainty (epistemic uncertainty is zero), while the sliding-plane method and the static analysis contain aleatory and epistemic uncertainties. The epistemic uncertainty is assumed to derive from the uncertainty of the analysis method.

In order to identify the relation between the standard values and the probability of failure, the relation between the results of the dynamic analysis and those of the sliding-plane or the static analysis are used for the calibration. The basic concept of the calibration is shown in Fig. 2. We assume that the results of the dynamic analysis are true, which means the epistemic uncertainty is zero. This indicates there is no uncertainty with the analysis method in evaluating failure. Also, the log-normal distribution is assumed because the sliding failure safety factor is always positive or zero. The failure probability is defined as a probability less than S_f=1.0, and is given by

$$P_f = \Phi\left[\frac{\ell n S_f\big|_{CR} - \lambda_D}{\zeta_D}\right] \quad (3)$$

where, λ_D and ζ_D are the mean and standard deviations of $ln\, S_f$ for the dynamic analysis, and Φ act as a cumulative distribution function. $S_f\big|_{CR}$ is a critical safety factor under conditions where the structure is damaged. Because design is generally carried out using the mean value of material properties, we assume that the mean values of S_f are equal to the standard values. That is, the mean values are 1.5 for the foundation ground and 1.2 for peripheral slopes. Therefore, once we assume the probability of failure, P_f, ζ_D is evaluated by the following equation.

$$\zeta_D = \Phi^{-1}[P_f]\left\{1-\sqrt{1+\frac{2\ell n \mu_D}{\Phi^{-1}[P_f]^2}}\right\} \quad (4)$$

We can then assume that the failure probability by the dynamic analysis is equal to the probability by both the sliding-plane method and the static analysis. In addition, the sliding-plane method and the static analysis contain the uncertainty of the analysis method, ζ_U. The ζ_U is obtained by the questionnaire investigation shown in the next section. Thus, the uncertainty of the sliding-plane method and the static analysis is written as

$$\zeta_S = \sqrt{\zeta_D^2 + \zeta_u^2} \quad (5)$$

From the above assumption, the mean value of S_f for the sliding-plane method and the static method can be estimated by the following equation.

$$\mu_S = exp\left[-\Phi^{-1}[P_f]\sqrt{\zeta_D^2+\zeta_u^2}+\frac{1}{2}\left(\zeta_D^2+\zeta_u^2\right)\right] \quad (6)$$

From μ_S obtained by the above equation, the standard value can be estimated by multiplying the ratio of analysis methods (sliding-plane/dynamic or static/dynamic). Once the probability of failure, P_f, is assumed, one can estimate thecorresponding standard values for the sliding-plane and the static analysis using Eq. (4) and (6). The estimation process is performed periodically for the different failure probabilities. The failure probability can then be identified as the standard value. That is, the probability of failure at a safety factor of 1.5 for foundation ground and 2.0 for peripheral slopes is as shown by the calibrated results.

3.2. Uncertainty of analysis

In the previous section, the procedures for the calibration were derived. In the procedures, the uncertainty of the analysis method should be determined before calibration is performed. This calibration study uses the results of a questionnaire survey of electric power companies operating nuclear power plants and includes 131 analysis sections (9 sites).

Fig. 3 shows a comparison of sliding failure safety factors. The statistical data of the safety factors evaluated by three methods is listed in Table 2. Safety factors for the dynamic analysis showed a tendency to be greater than those for the sliding-plane method and the static analysis. In addition, the coefficient of variation for the sliding-plane method is larger than that for the static analysis. ζ_U of 0.335 for the sliding-plane and the ζ_U of 0.265 for the static analysis are used as the uncertainty of the analysis method in Eq. (6). The mean values are also used for correcting the differences in the analysis method.

3.3. Results and discussions

The relations between the safety factors and failure probabilities are estimated based on the above procedures and the data from the questionnaire survey. Fig. 4 shows the results of the calibration. Since the safety evaluation standard values for foundation ground is presently 2.0 against S_2 ground motion, failure probability due to the S_2 is obtained from the figure. A safety factor of 1.5 is the corresponding point for peripheral slopes.

To obtain annual the probability of failure occurrence, the probability of ground motion should be specified. The occurrence probability of basic ground motion S_2 is assumed to be $1.0*10^{-5}$ - $5.0*10^{-4}$ [1/year] in JEAG4601 (Supplement)-1987. Thus, the annual probability of failure for structures, which satisfies present safety standards, can be evaluated as conditional failure. The results of calibration are listed in Table 3. The results show that the annual probability of failure is sufficiently low. Therefore, a structure appears to be sufficiently safe when it satisfies current safety evaluation standard values. Also, the annual probability of failure for peripheral slopes is greater than that for foundation ground.

The Nordic Code, which is used as reference for the discussion, indicates the partial coefficient to be adopted for a maximum failure probability depending on the safety class and type of failure shown in Table 4. Note that the safety requirements are dependent on the safety class, and the difference of one safety class results in a 10 fold difference in failure probability. Based on the difference in the table it was found that foundation ground is placed in a higher class than peripheral slopes. These results are also consistent with the classification of structures.

4. Conclusions

This paper presents the procedures and results of calibration of evaluation standard values for seismic stability of foundation ground and peripheral slopes for nuclear reactor buildings. It was found that the current safety evaluation standard values allow a probability of failure that is sufficiently low. Also, it confirms that the safety class of foundation ground is one rank higher than that of peripheral slopes.

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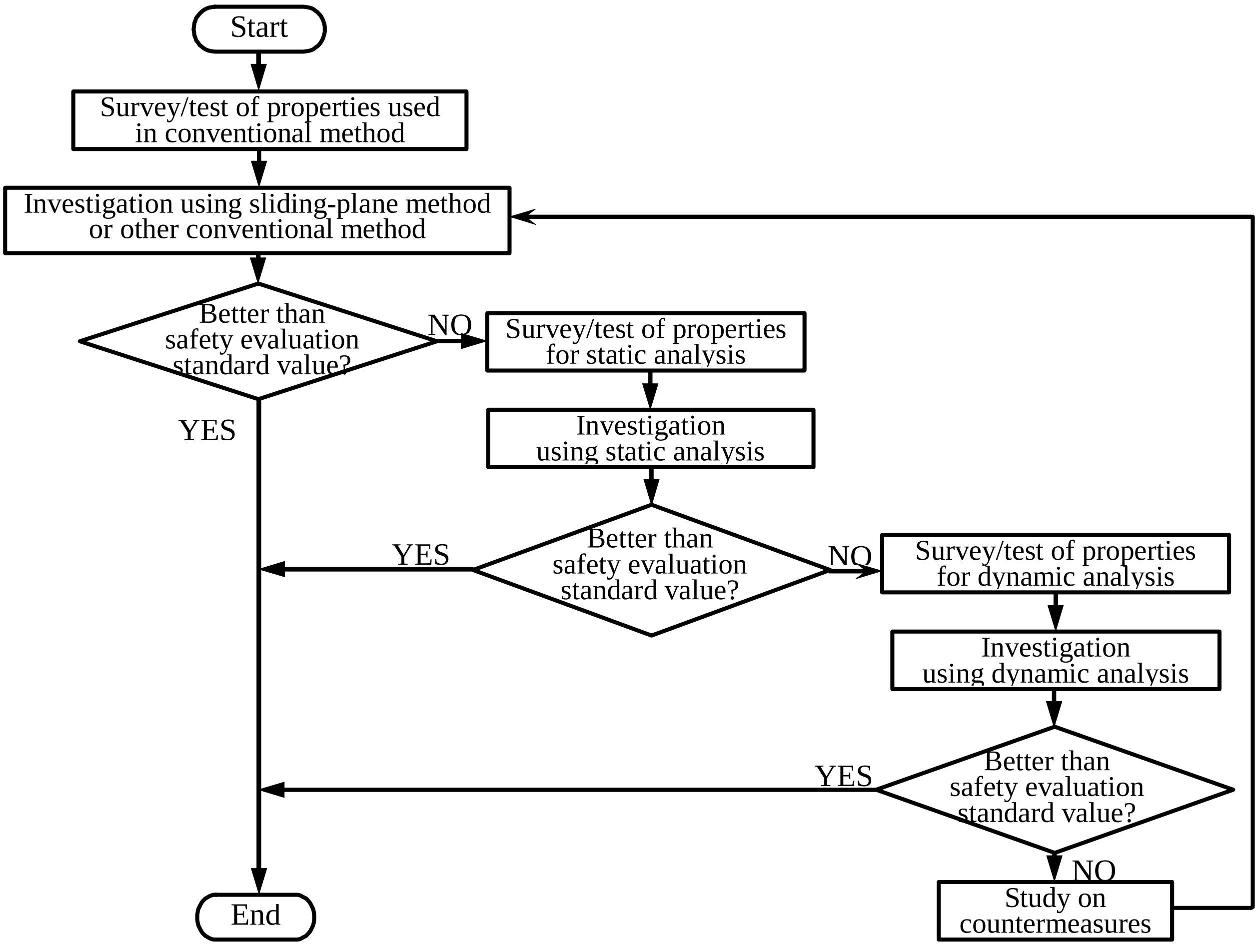


Figure 1: Flowchart of safety evaluation

Table 1: Evaluation standard values

Structure	Analytical method		
	Sliding-plane method	Static analysis	Dynamic analysis
Foundation ground	2.0	2.0	1.5
Peripheral slope	1.5	1.5	1.2

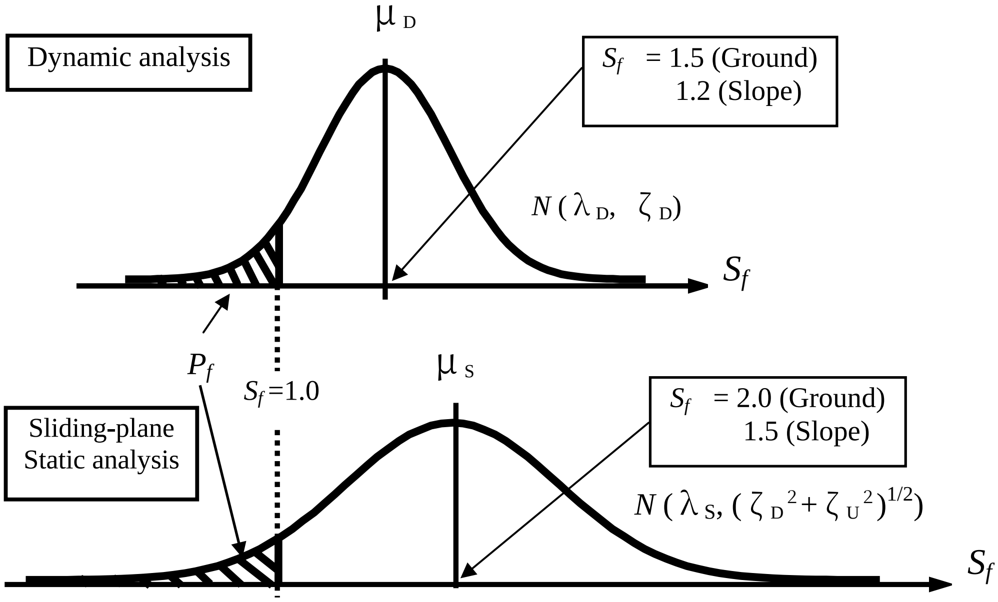


Figure 2: Concept of calibration

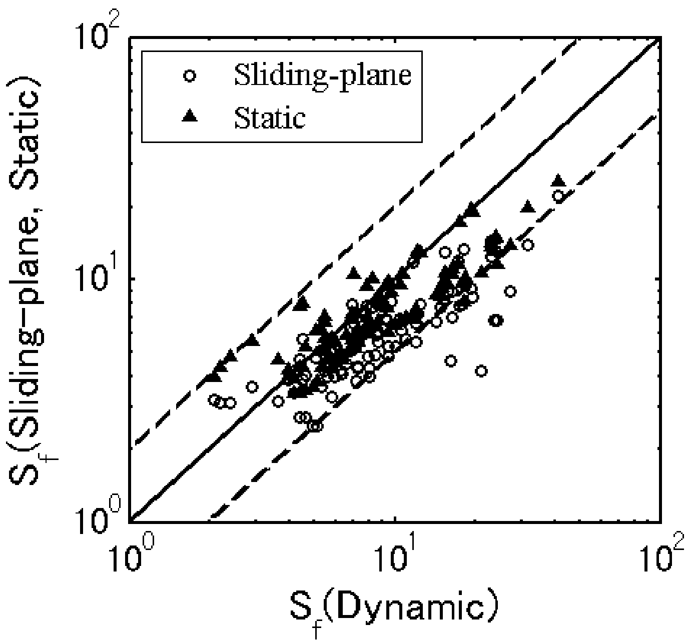
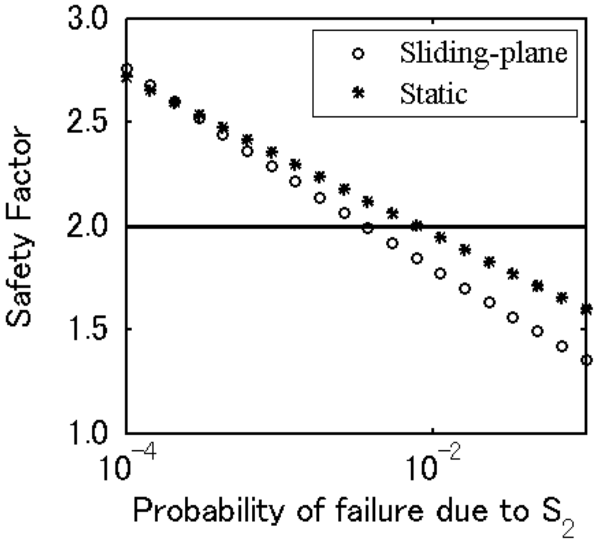


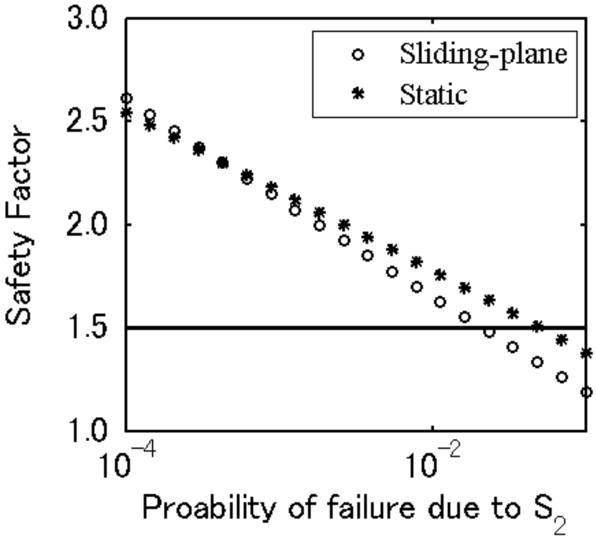
Figure3: Comparison of safety factors

Table 2: Mean and variation between analysis methods

	Safety factor	
	Sliding-plane/Dynamic	Static/Dynamic
Mean	0.714	0.899
Median	0.680	0.823
Coefficient of variation	0.335	0.265



(a) Foundation ground



(b) Peripheral slopes

Figure 4: Required safety evaluation standard values

Table 3: Annual probability of failure

	Foundation ground	Peripheral slope
Failure probability due to S_2 ground motion	$3.60*10^{-3}$ - $7.91*10^{-3}$	$2.13*10^{-3}$ - $5.01*10^{-3}$
Occurrence probability of S_2 ground motion	$1.0*10^{-5}$ - $5.0*10^{-4}$	
Annual probability of failure	$3.60*10^{-8}$ - $3.96*10^{-6}$	$2.13*10^{-7}$ - $2.51*10^{-5}$

Table 4: Nordic Committee Safety requirements

Failure consequences (Safety class)	Ductile failure with remaining capacity	Ductile failure without remaining	Brittle failure
Less serious (Low safety class)	$P_f \leqq 10^{-3}$	$P_f \leqq 10^{-4}$	$P_f \leqq 10^{-5}$
Serious (Normal safety class)	$P_f \leqq 10^{-4}$	$P_f \leqq 10^{-5}$	$P_f \leqq 10^{-6}$
Very serious (High safety class)	$P_f \leqq 10^{-5}$	$P_f \leqq 10^{-6}$	$P_f \leqq 10^{-7}$