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

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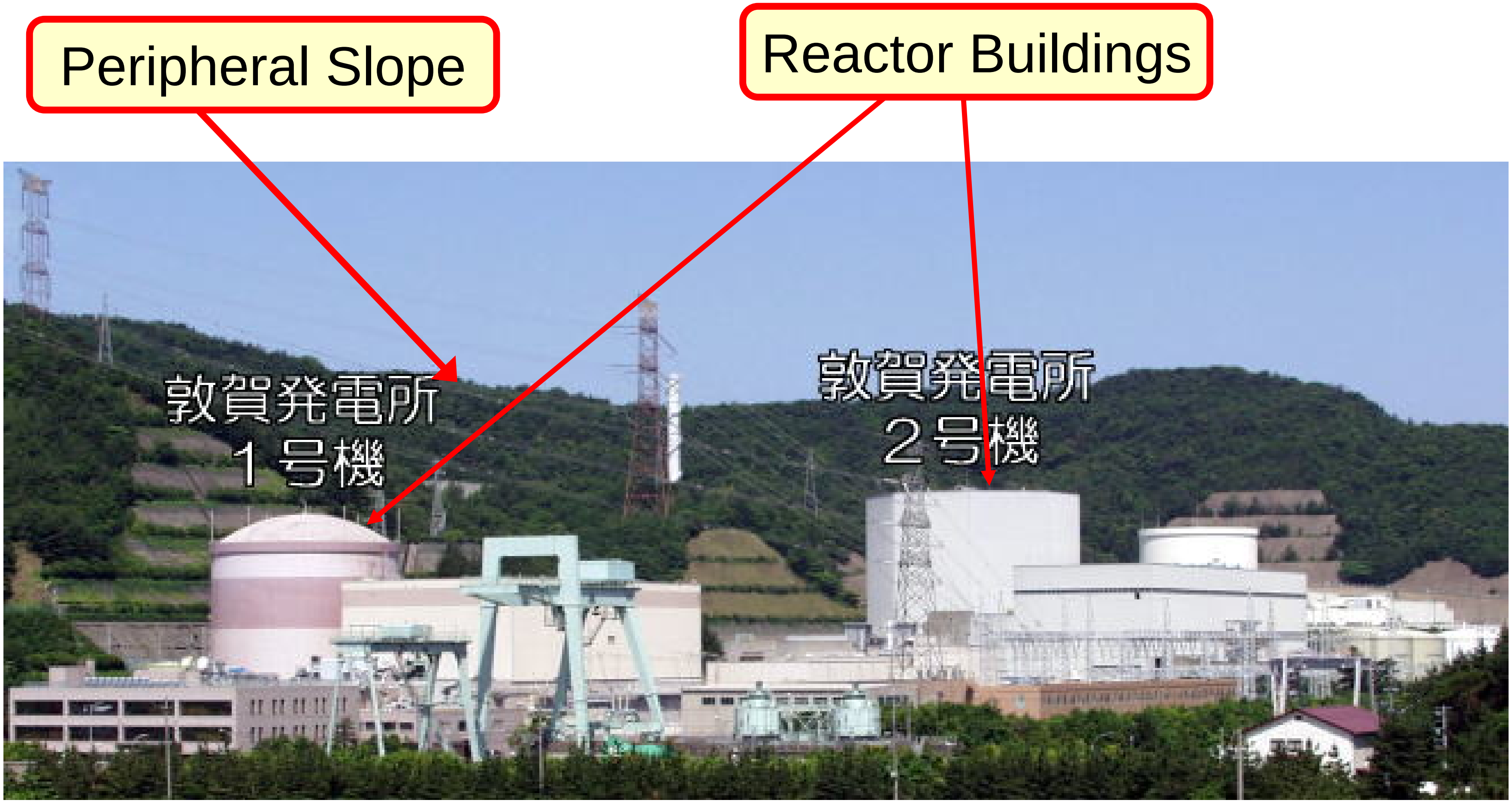
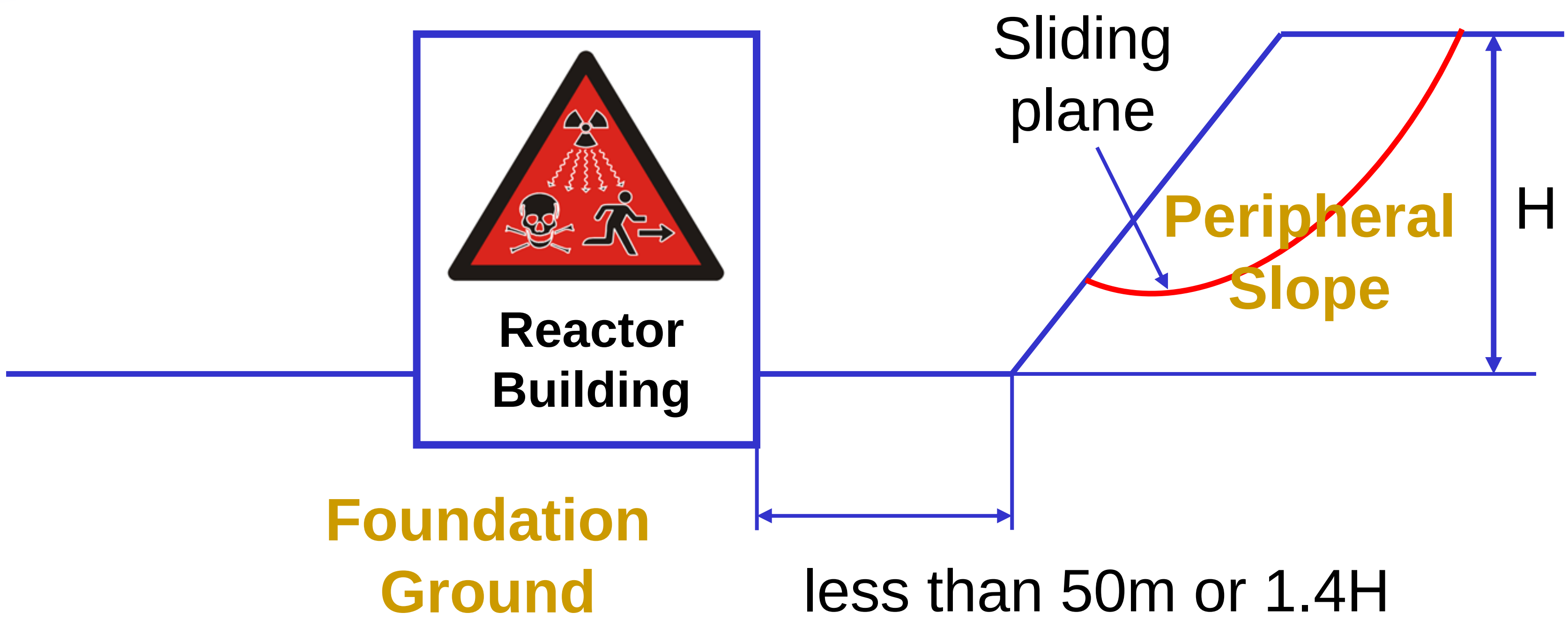
Example Nuclear Power Plant



BWR PWR

http://www.japc.co.jp/tsuruga/plant_guide/index.htm

Definition of Structures



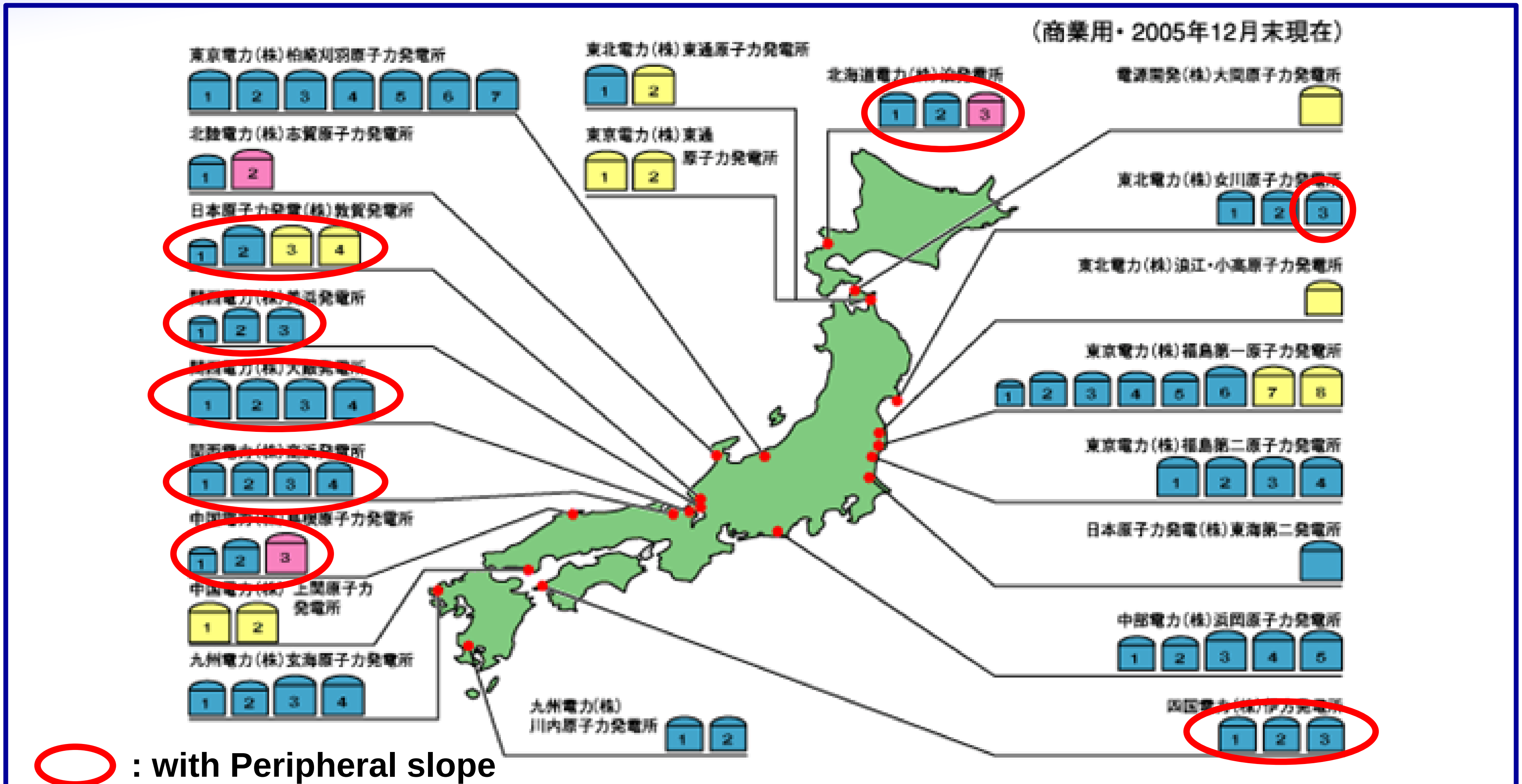
■**Foundation Ground:**

Support the buildings and structures containing radioactive substances

■**Peripheral Slope:**

The slope has a distance between its tail and the nuclear reactor building shorter than about 50m or shorter than about 1.4 times the slope height

Nuclear Power Plants in Japan



	基数	合計出力(万kW)
運転中	54	4,822.2
建設中	3	364.3
着工準備中	11	1,494.5
合計	68	6,681.0

出典:「原子力・エネルギー」図面集　2005-2006　4-4

Background

- **Regulatory Guide for Aseismic Design for NPP in Japan**

  June, 2001: Revision work stared under NSC (Nuclear Safety Commission)

  Sept. 19, 2007: Revised aseismic regulatory guides issued

- **Technical Guideline for Aseismic Design (JEAG)**

  Revision work (Continue)

- **Seismic PSA manual in Japan**

  March, 2004: Start Seismic PSA committee

  March, 2007: Final decision on publication

Objective

How safe is a structure satisfied the current criteria?
Are the criteria appropriate?

Criteria for
design and/or evaluation

Engineering judgment

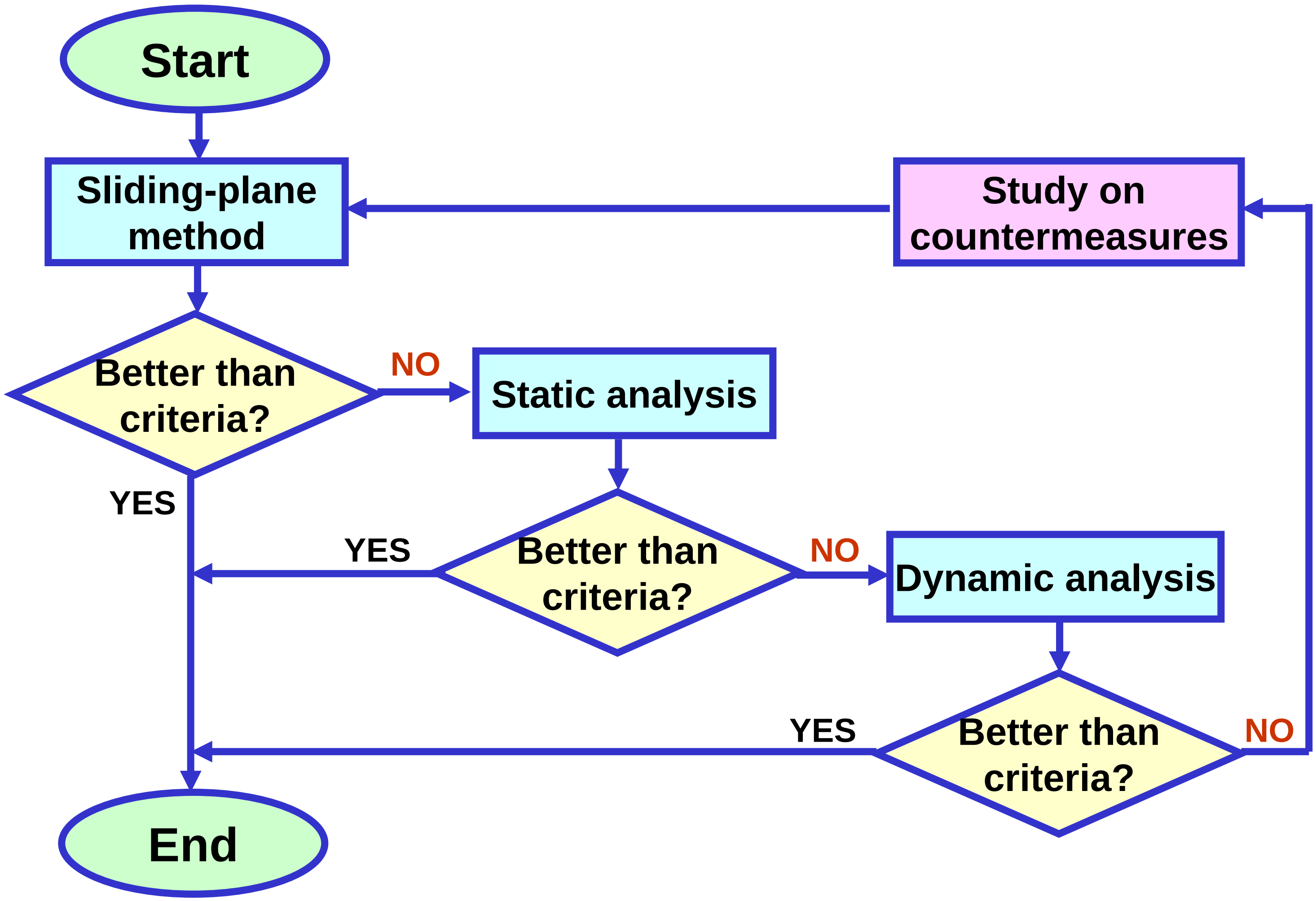
Accumulated knowledge

Questionnaire Survey

Calibration

Annual probability of failure

Flowchart of Safety Evaluation



Currently, all three methods should be performed in JEAG!

Safety Evaluation Standard Values

■Criteria against S_2(Safety 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

■Sliding Failure Safety Factor (Calculated value)

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

■Judgment

Standard value < Fs : Safe

Standard value > Fs : Collapse

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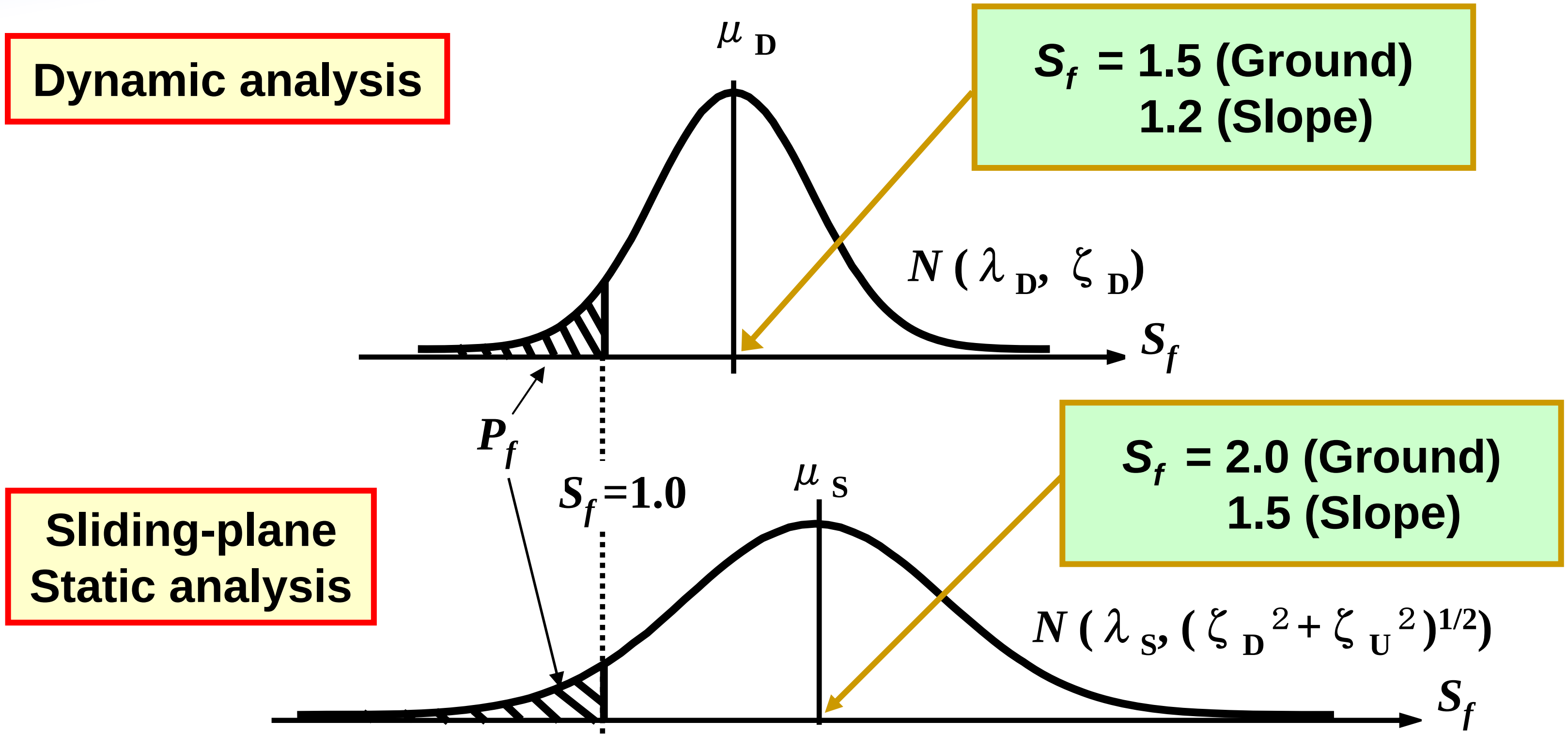
Concept of Calibration



Analysis method	Uncertainty	
	Aleatory	Epistemic
Dynamic	$\zeta_D \neq 0$	Zero
Static, Sliding-plane	ζ_D	ζ_U

Additional assumptions

- Mean values of properties are used in the safety evaluations
- Log-normal distributions of sliding failure safety factor
- Mean values of sliding failure safety factor

$$E\left[S_f\left(x_1, x_2, \cdots, x_n\right)\right] \cong S_f\left(\bar{x}_1, \bar{x}_2, \cdots, \bar{x}_n\right)$$

Random variables

Mean values

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Procedure (I)

Failure Probability

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

λ_D and ζ_D : Mean and standard deviation of $ln\ S_f$ for the dynamic analysis

Φ : Cumulative distribution function

$S_f|_{CR}$: Critical Safety Factor (=1.0; $S_f < S_f|_{CR}$: Damaged)

ζ_D is given by

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

μ_D : Mean value of S_f

Procedure (II)

Relation of failure probabilities (not dependent on analysis method)

$$\Phi\left[\frac{\ell n S_f\big|_{CR} - \lambda_D}{\zeta_D}\right] = \Phi\left[\frac{\ell n S_f\big|_{CR} - \lambda_S}{\zeta_S}\right]$$

where,

$$\zeta_S = \sqrt{\zeta_D^2 + \zeta_u^2}$$

Analysis method	Uncertainty	
	Aleatory	Epistemic
Dynamic	$\zeta_D \neq 0$	Zero
Static, Sliding-plane	ζ_D	ζ_U

Thus,

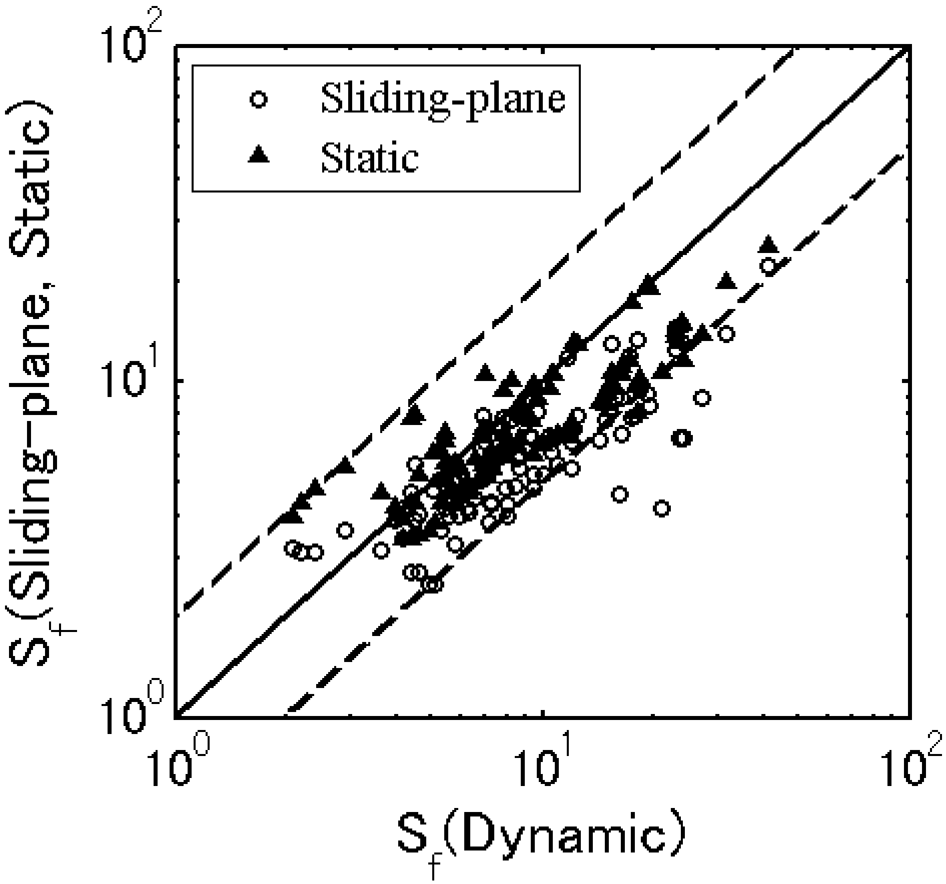
$$\mu_S = \exp\left[-\Phi^{-1}\left[P_f\right]\sqrt{\zeta_D^2 + \zeta_u^2} + \frac{1}{2}\left(\zeta_D^2 + \zeta_u^2\right)\right]$$

$$S_f\big|_s = \mu_S \cdot E\left[S_f^{(S)}\right] / E\left[S_f^{(D)}\right]$$

From questionnaire survey

where, $S_f|_s$ is safety evaluation standard value for the sliding-plane method and the static analysis

Sliding Failure Safety Factor Statistical Data



Number of sites: 9

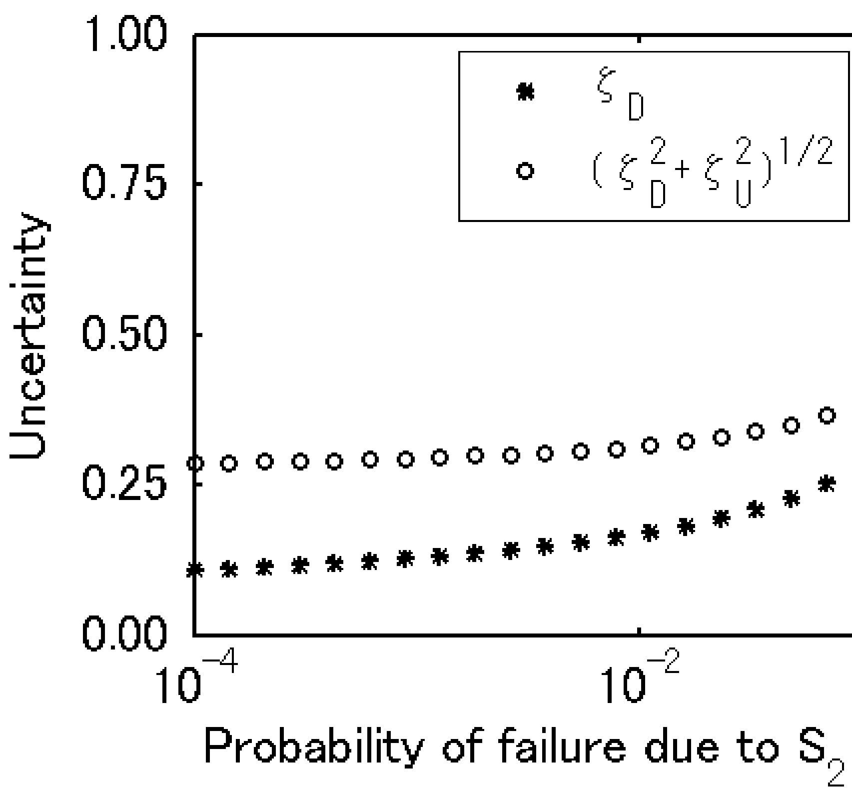
Number of samples: 131

	Safety factor	
	Sliding-plane/Dynamic	Static/Dynamic
Mean	0.714	0.899
Median	0.68	0.823
Coefficient of variation	0.335	0.265

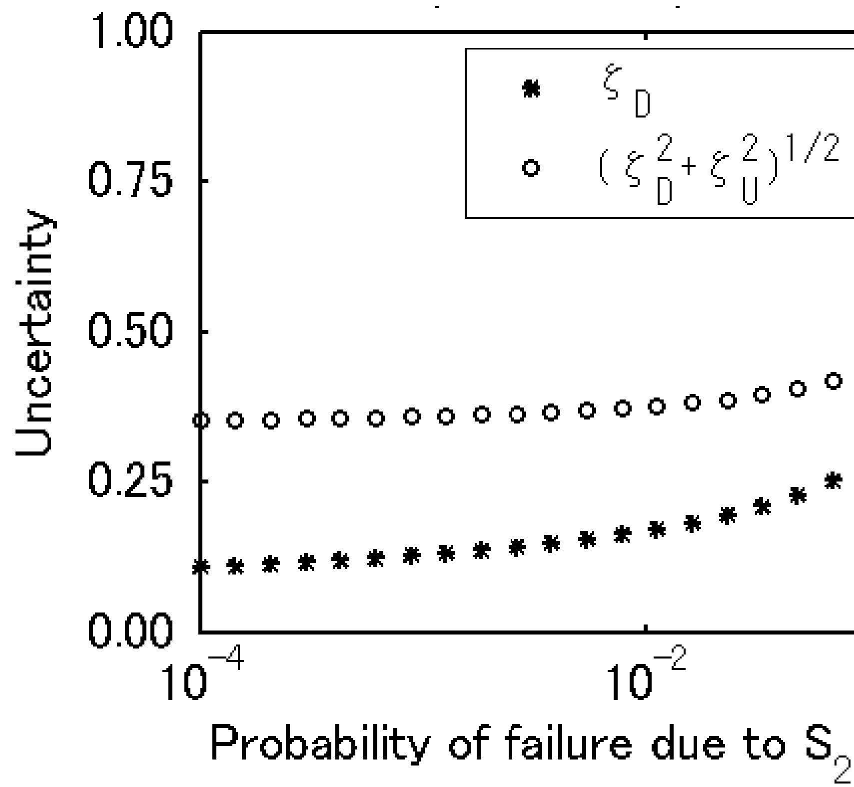
Calibration Results (I)

- Uncertainty -

Foundation Ground



Peripheral Slope



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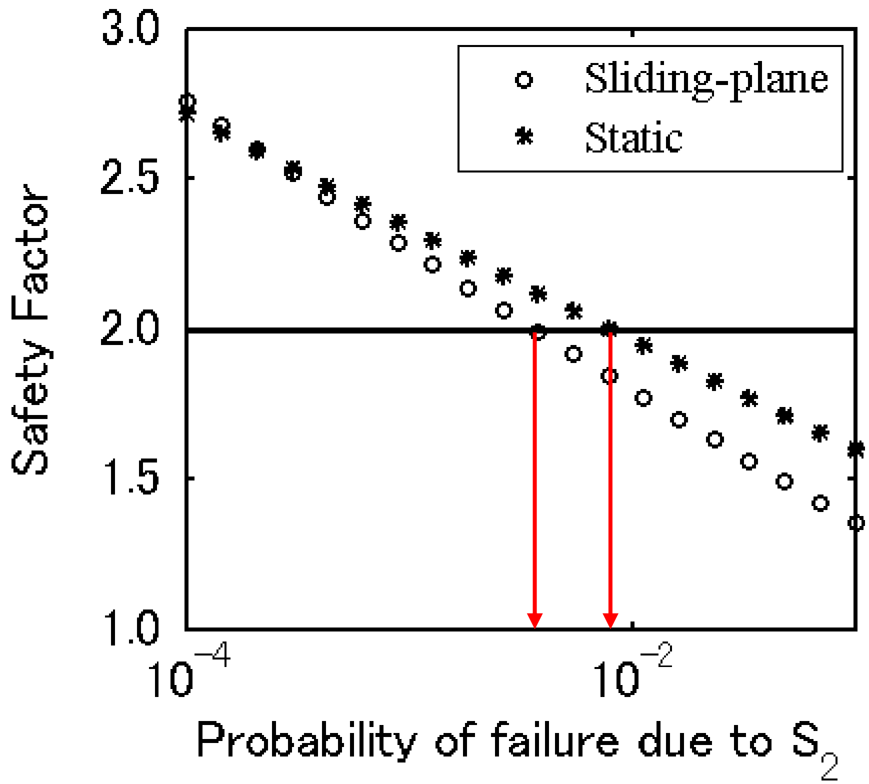
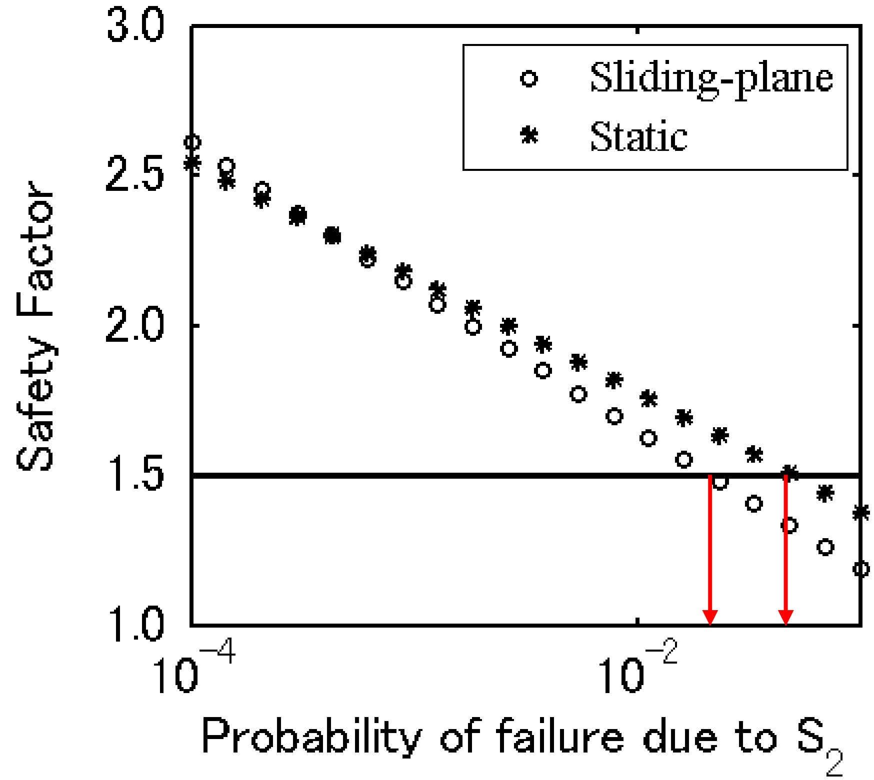
Calibration Results (II)

- Probability of Failure -

Foundation Ground



Peripheral Slope



Occurrence Probability of Design Earthquake

◆ JEAG4601・Supplement-1984

Occurrence probability of the basic ground motion, S_2, is 10^{-4}～10^{-5} in the Technical Guideline. However, in the JEAG4601・Supplement-1984, the occurrence probability of 5×10^{-4}～10^{-5}/site・year is used.

◆ IAEA Safety Standards Series (Safety Guide)

Seismic Design and Qualification for Nuclear Power Plants

SL-1 (for Load Combination): 1×10^{-2} (mean) [event/reactor/year]

SL-2* (Design Basis Earthquake): 1×10^{-3}～1×10^{-4} (mean)

or 1×10^{-4}～1×10^{-5} (median)

*) Corresponds to a safe shutdown earthquake level.

Calibration Results (II)

- 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	$3.60*10^{-8}$ - $3.96*10^{-6}$	$2.13*10^{-7}$ - $2.51*10^{-5}$

about 1/10

Nordic Committee Safety Requirements

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

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Calibration Results (II)

- Probability of Failure -

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Conclusions

- **Devised a calibration procedure for safety evaluation standard values for foundation ground and peripheral slopes**

- **Demonstrated the calibration process and obtained the following results**
  - Structures designed with standard values are sufficiently safe.
  - Safety class of foundation ground is one rank higher than that of peripheral slope.

Thank you!