Slope Stability Assessment for Siting New Reactors

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The 1st Kashiwazaki International Symposium
Kashiwazaki, Japan, November 24-26, 2010

US Regulation

- 10 CFR 100.23 Geologic and seismic siting criteria, Section d (4) states that

  "Siting factors for other design conditions that must be evaluated include … natural and artificial slope stability…"

US Regulatory Guide

Regulatory Guide 1.206

2.5.5, Stability of Slopes

The applicant should present information concerning the static and dynamic stability of all natural and manmade earth or rock slopes (such as cuts, fills, embankments, and dams) for which failure, under any of the conditions to which they could be exposed during the life of the plant, could adversely affect the safety of the nuclear power plant facilities.

Slope Stability Assessment

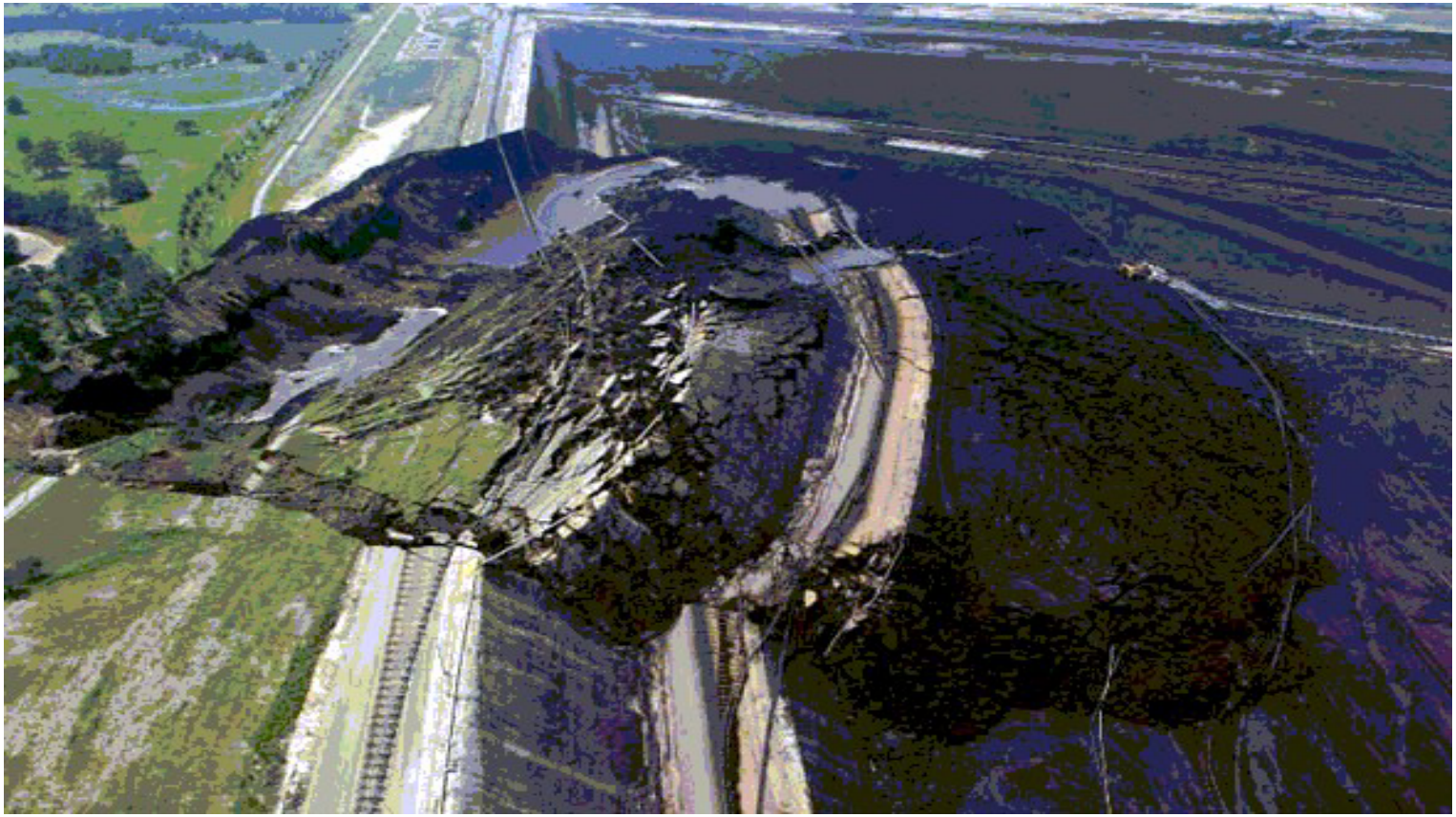
- Factors to be considered:
  - Types of slope failure
  - Models
  - Input for slope stability analysis
  - Design criteria

Types of Slope Failure

Global slope failure:
Entire slope section fails, landslide, etc.

Local slope failure:
portion of the slope fails

Global Slope Failure Example



Landslide Trigged by October 25, 2004 Niigata Earthquake

Local Slope Failure Example

Models

- Infinite slope without seepage
- Infinite slope with seepage
- Finite slope with planar failure surface
- Circular failure in homogeneous clays

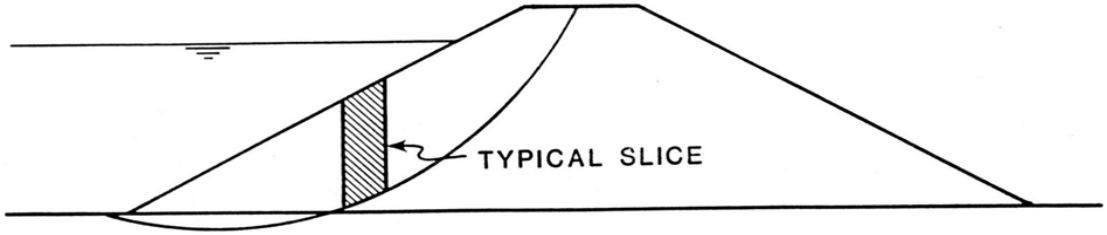
Infinite Slope Analysis

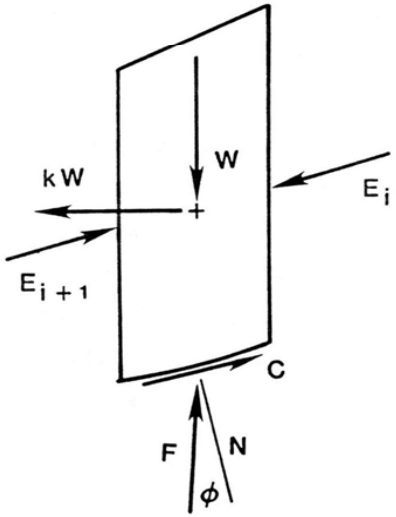
The failure is translational along a single plane failure surface parallel to slope surface. This type of analysis is typically applicable for surface raveling in granular materials .

Finite Slope Analysis

A finite slope analysis can be for a failure surface that is plane, circular, or non-circular. In a plane failure, the translational block slides along a single plane of weakness (or a geological interface).

Basic Concept





Franklin & Chang 1977

Commonly Used Models

- Moment equilibrium method
- Force equilibrium method
- Combination of force and moment equilibrium method
- Finite Element Model

Input for Slope Stability Analysis

- Site conditions
- Geometry of the slope
- Geological features and material of the slope
- Shear strength of soils
- Pore water pressure distribution

Input for Slope Stability Analysis (continued)

- Loadings
  - Dynamic loads, including seismic loading, Tsunami wave, etc.
  - Static loads (any surcharges)
  - Hydraulic pressure
  - Others

Design Criteria

- Factor of Safety (FS)

  FS = Capacity/Demand

  – Capacity is resisting shear strength and Demand is driving force acting on the potential slip surface
  – FS is not a measure of stability at a point, and it represents averaging effect
  – FS cannot be measured in the field
  – FS is model-dependent

Design Criteria (continued)

- Probability of failure, reliability of slope stability
  - Can capture uncertainties involved in slope stability analysis
  - Provide more confidence on the analysis results

Model Limitations

- Large uncertainties involved
  - Actual slope failure surface is irregular
  - Slope failure mechanism is not simple
  - Stress state changes along the slope slip surface
  - Finite element method has limitations

Model Limitations (continued)

- Seismic loading is just a prediction
- Great variation in soil property determination
- Many parameters/factors are time dependent, and nonlinear

Model Limitations (continued)

- Design criteria need to be improved
  - Factor of safety is an engineering measure and not unique for the same slope when using different models/methods
  - Probabilistic method currently is not accepted in real design, needs to be improved

Procedure to Assess Slope Stability for a New Reactor Site

- Screen slopes to be analyzed
- Determine slope and soil properties
- Determine loading conditions
- Choose analysis model
- Choose design criteria

Screening for Slopes to be Analyzed

- Survey the site and examine planned construction activities to identify all slopes, existing or new, permanent or temporary slopes
- Determine the slope(s) whose stability would directly or indirectly affect safety-related SSC

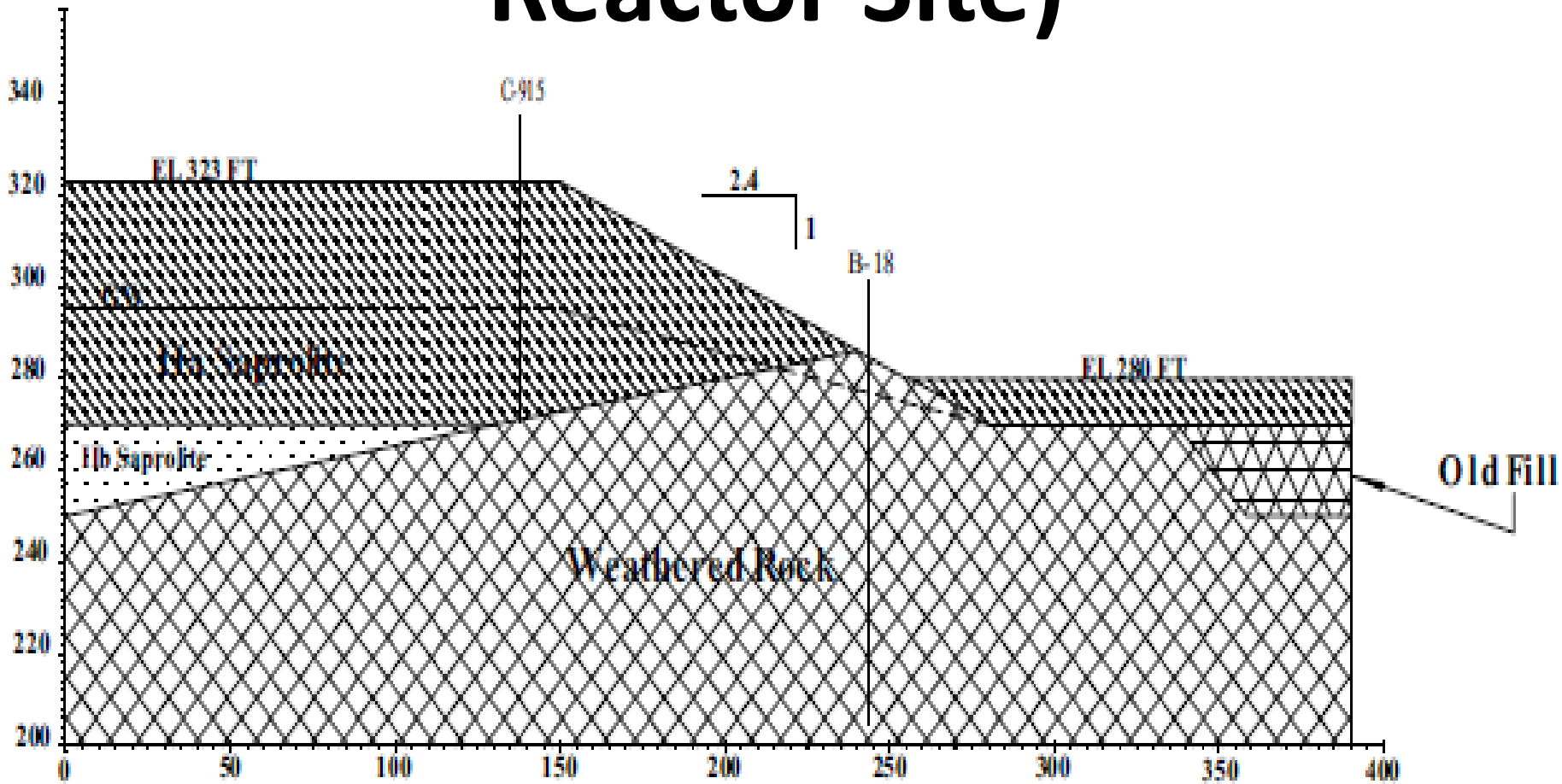
New Reactor Site -1

New Reactor Site -2

Determine Slope and Soil Properties

- Site survey to determine the topography of the slopes
- Site investigations to determine physical properties of the underlying material and ground water, seepage conditions
- Field and laboratory tests to determine engineering properties of the soil

Slope Cross Sections (a New Reactor Site)



Determine Loading Conditions

- Control earthquake needs to be properly identified
- Determine the PGA to be used in analysis based on performance-based site-specific earthquake ground motion response spectra.
- Determine any surcharges

Choose Analysis Model

- Traditional methods are normally used in slope stability analysis
- Commercially available computer software, such as GeoSlope and SLIDE, is normally used
- Carefully and conservatively choose input parameters

Choose Design Criteria

- Factor of Safety is commonly used as design criteria
  - FS > 1.5 for long-term static slope stability
  - FS > 1.1 long-term seismic slope stability

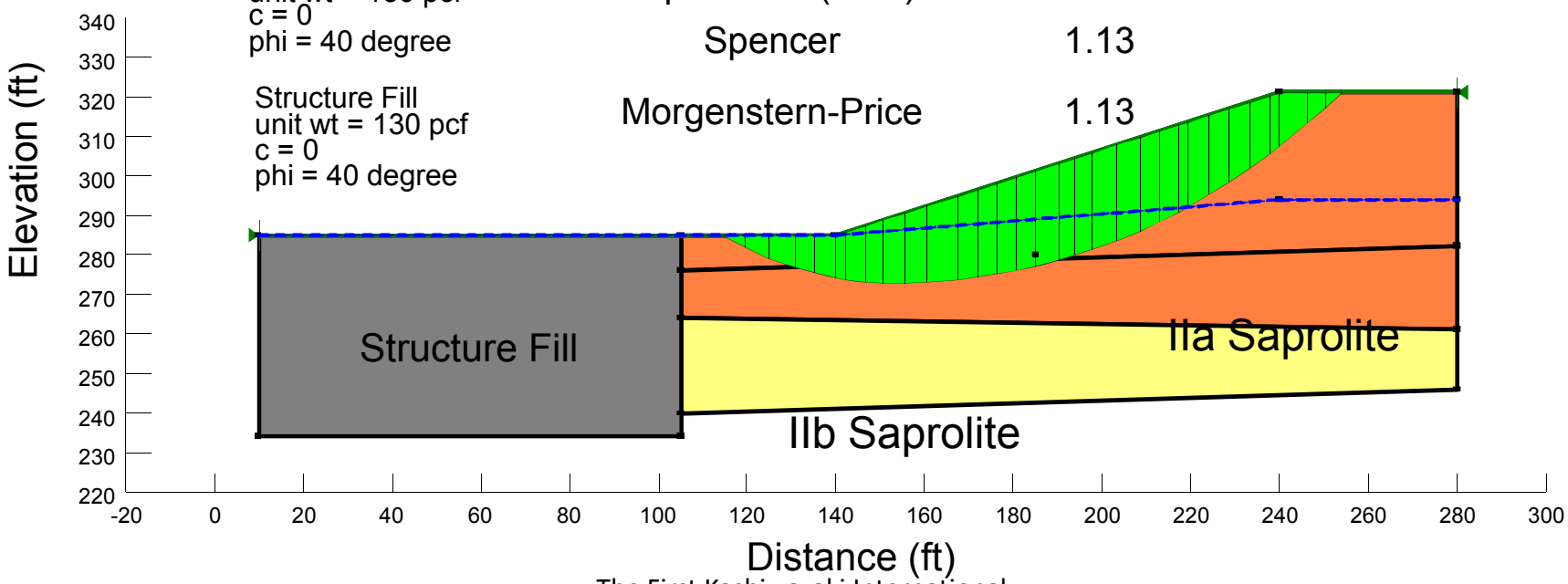
Slope Stability Analysis Example

IIa Saprolite
unit wt = 125 pcf
c = 125 psf
phi = 33 degree

IIb Saprolite
unit wt = 130 pcf
c = 0
phi = 40 degree

Structure Fill
unit wt = 130 pcf
c = 0
phi = 40 degree

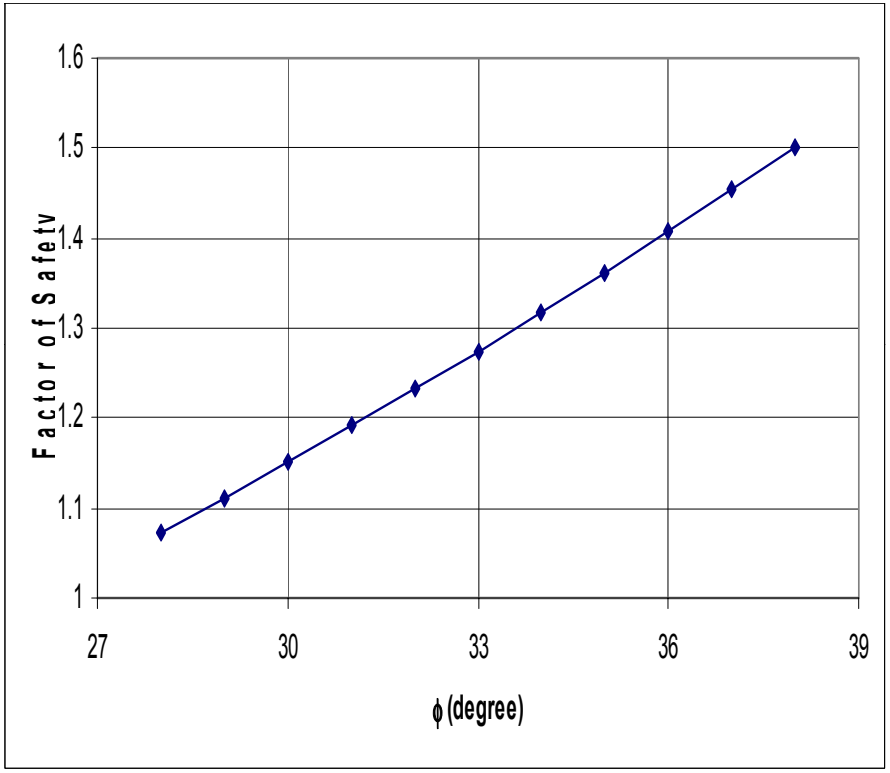
Method	FS - Seismic
Ordinary	1.11
Bishop	1.12
Janbu	1.05
General Limit Equilibrium (GLE)	1.13
Spencer	1.13
Morgenstern-Price	1.13



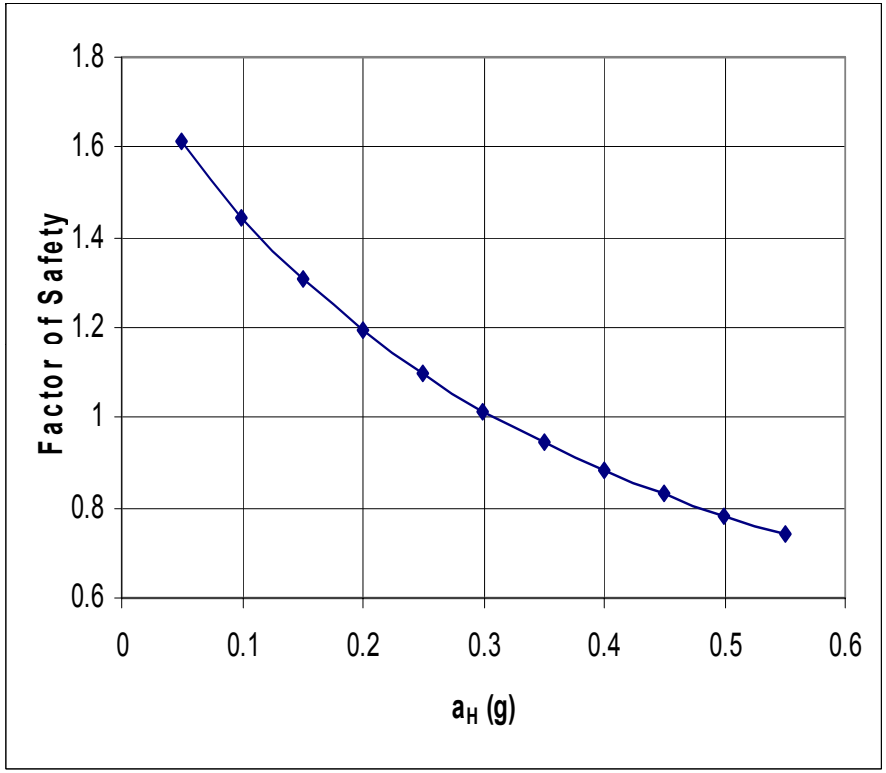
Other Factors in Slope Stability Assessment

- Earthquake induced settlement
  - Tokimatsu, K. and Seed, H.B. (1987)
  - Lee, C. Y. (2004)
- Reliability of FS

Sensitivity of FS to Input Parameter Variation



Effect of changing internal friction angle on factor of safety



Effect of changing Horizontal Seismic Load on factor of safety

Reliability of FS

Coefficient of variation of ground motion acceleration (%)	Mean of factor of safety	Standard deviation of factor of safety	Reliability index	Probability of FS<1.0 (%)
10	1.131	0.068	1.924	0.05
20	1.141	0.112	1.263	6.15
30	1.147	0.154	0.954	17.30
40	1.154	0.189	0.815	21.30
50	1.152	0.235	0.647	28.65
100	1.115	0.317	0.363	43.50

Summary and Conclusions

- Slope stability assessment is one of the important elements in new reactor siting evaluation
- Current practice can provide good estimate of the slope stability if conservative approach is used
- Model and design criteria for slope stability assessment need to be improved

Thank you
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