Temasdag Jordskjelv

Slope Stability Part 1 – Theory and Methods

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1 November 2022

Outline

- Triggers and types of failures
- Input parameters
- Methods
  - Pseudo-static
  - Displacement based
  - Non-linear dynamic
- Eurocode 8 guidelines
- Important considerations

Las Colinas, Santa Tecla, El Salvador, 13 January 2001 (USGS)

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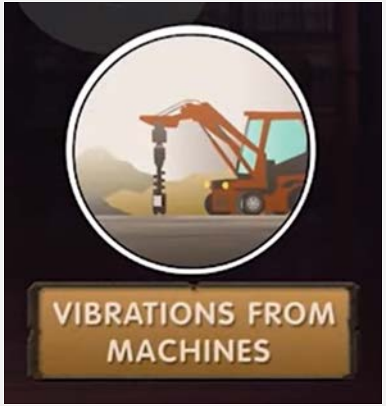
Triggers

- Earthquakes
- Rainfall
- Sedimentation
- Erosion
- Human induced
  - Blasting
  - Construction
  - Removal of vegetation



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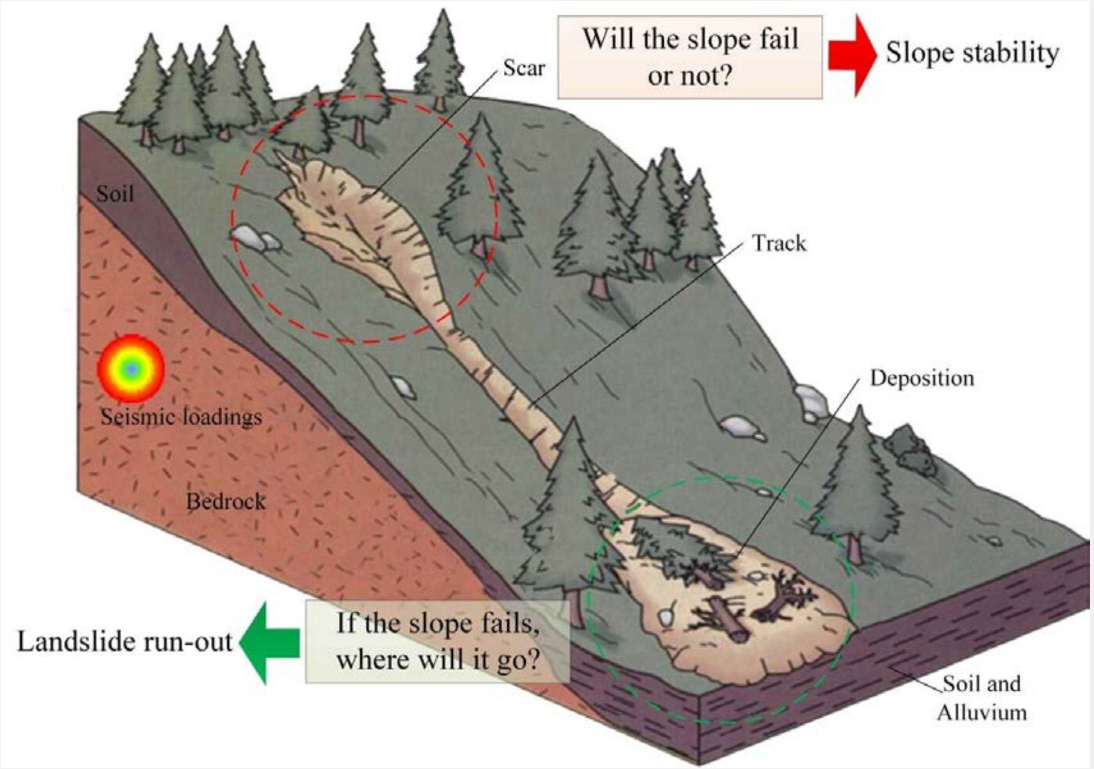
https://www.youtube.com/watch?v=MoWj6xttRKY

Types of Failure

- Flow slide: materials that lose significant strength as a result of cyclic loading (liquefaction, sensitive soils), long runout
- Seismically induced deformations: soil does not lose strength but may still have deformations that jeopardize system performance due to earthquake shaking



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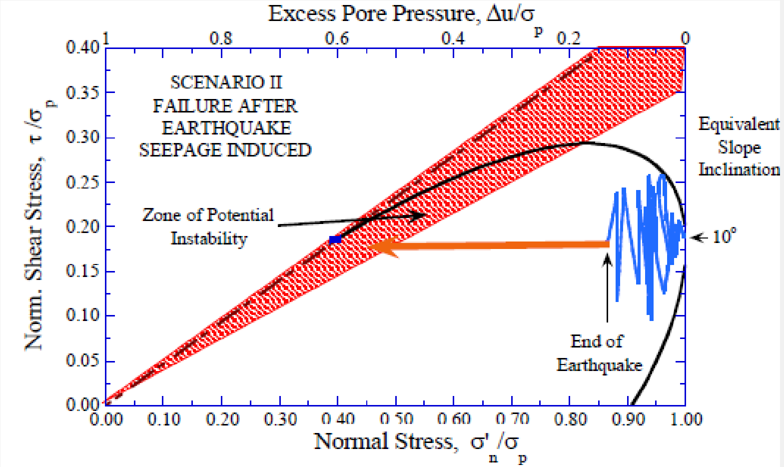
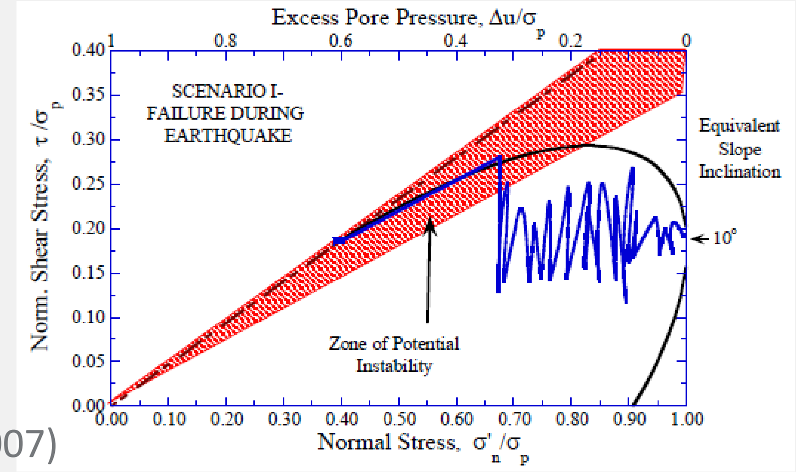
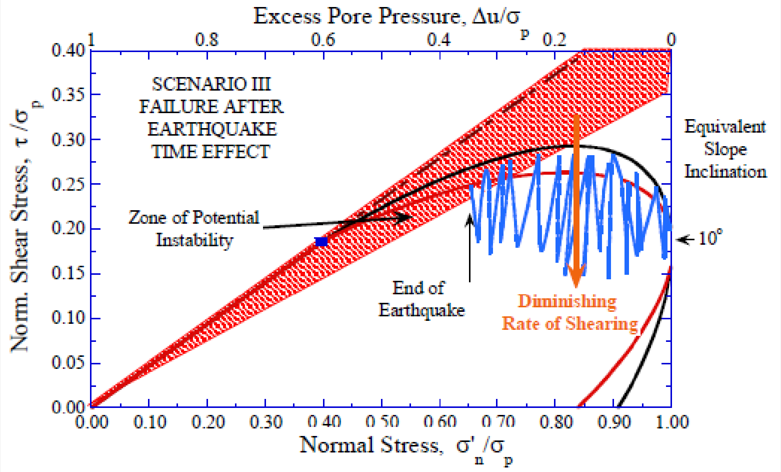
Earthquake Failure Scenarios

- Failure during the earthquake due to degradation of the shear strength
- Post earthquake failure due to migration of excess pore pressures
- Post earthquake failure due to creep or reduction of static shear strength





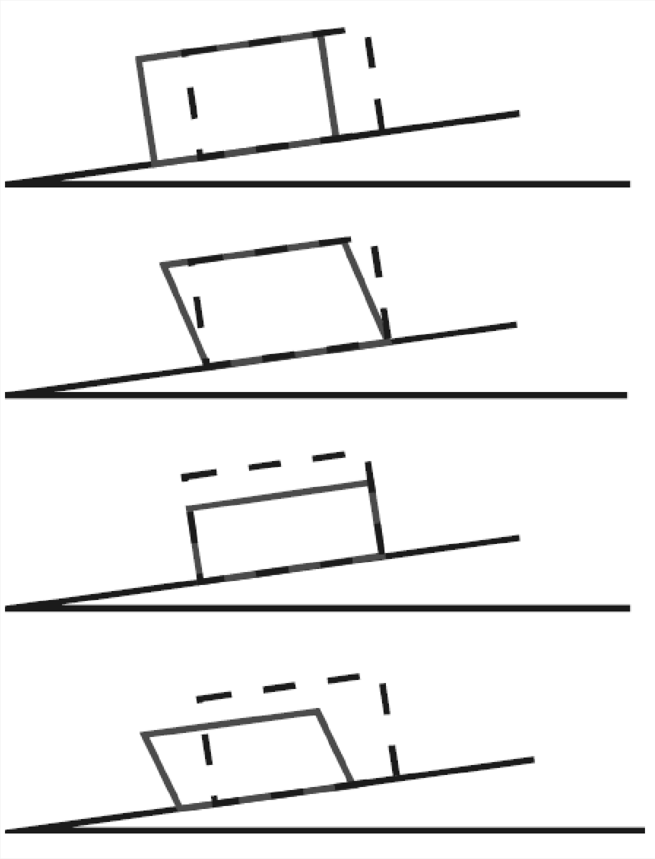


Nadim et al. (2007)

Mechanisms

Mechanisms contributing to slope displacements:

- Slip along a distinct failure surface
- Distributed deviatoric shear deformation
- Volumetric deformation
- Combined effects



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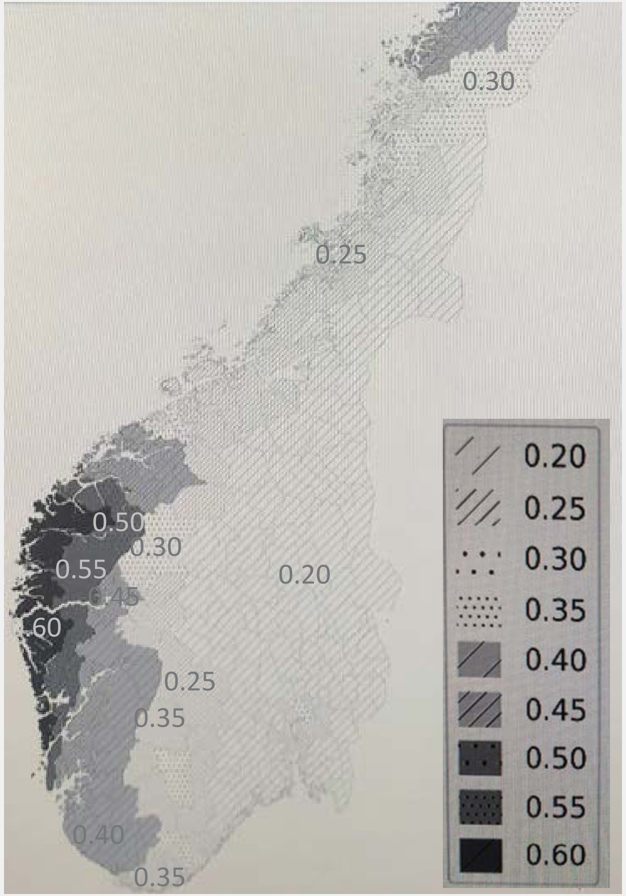
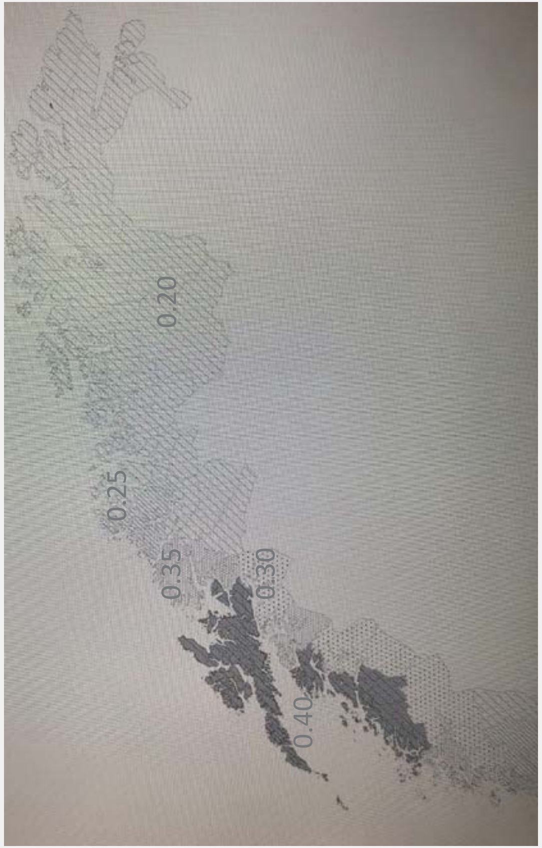
Components

- Ground motion
  - PSHA
  - Codes
- Soil properties
  - Site investigation
  - Laboratory testing
  - Literature review
- Geometry of slope
  - Site investigation
  - Geologic maps





a_{gR} in m/s^2 for 475 year return period (Eurocode 8 NA, 2021)

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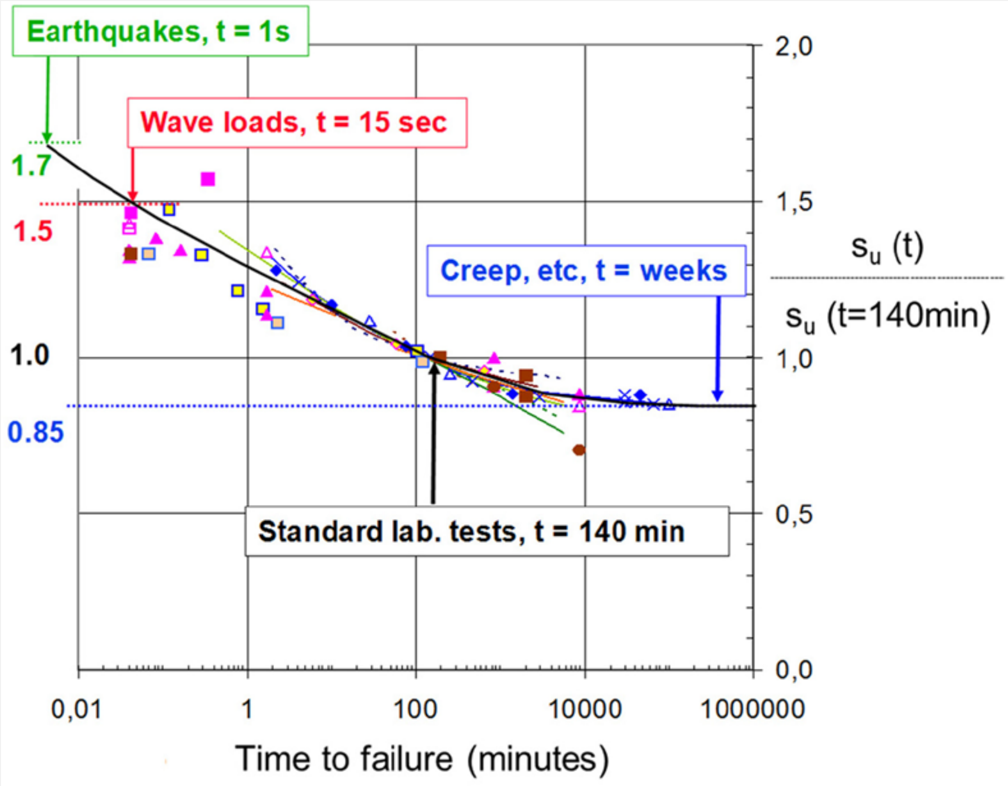
Dynamic Soil Strength

- Rate effects increase shear strength in cohesive soils
- Cyclic softening decreases shear strength due to increase in pore pressure and destruction of soil fabric
- RIF (Løset, 2010) recommend 30%-40% increase for strain-rate effects and 15 %, 20 % and 25 % reduction for cyclic degradation for importance classes I-II, III and IV, respectively.



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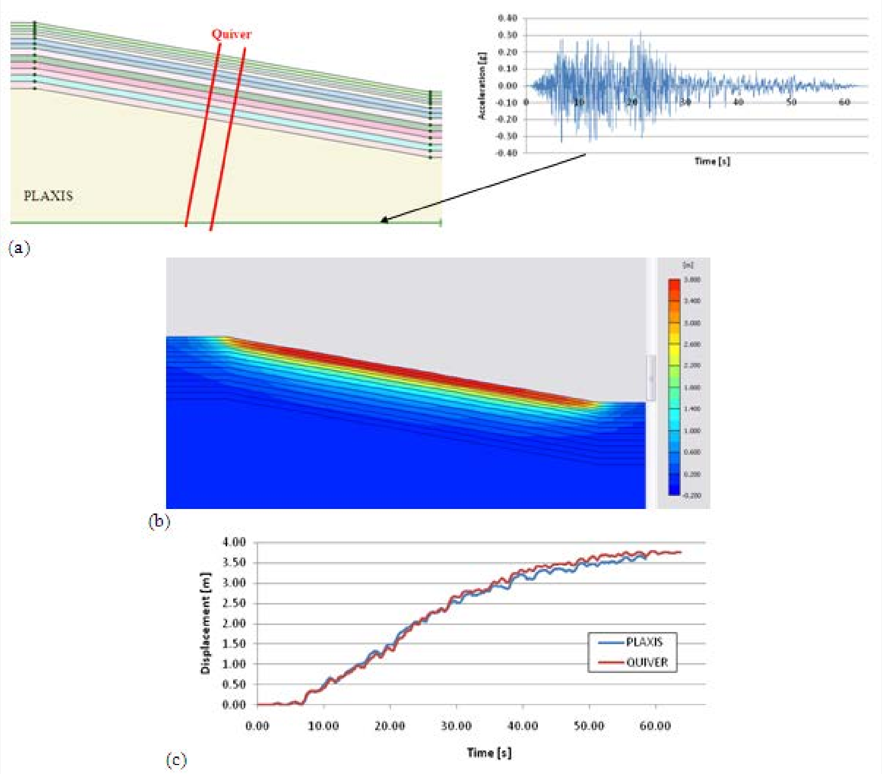
Andersen 2015

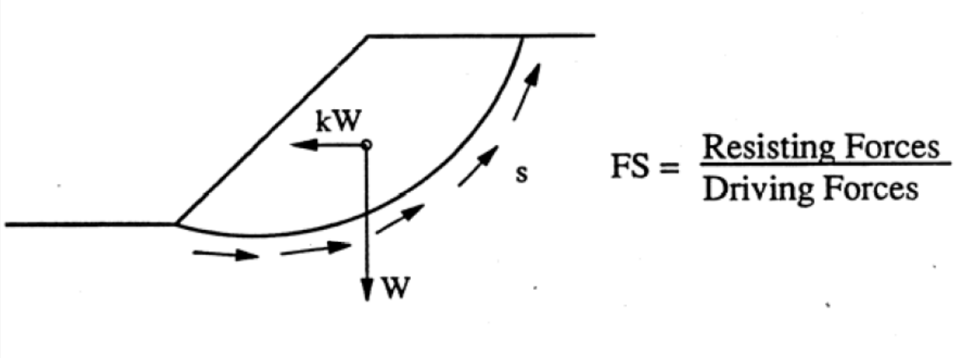
Methods of Analysis

- Pseudo-static analysis
  - Infinite slope
  - Limit equilibrium
  - FEM
- Displacement based analysis
  - Newmark sliding block
  - Simplified displacement models
- Non-linear dynamic analyses
  - 1D, 2D, 3D
  - FEM, FDM



Pseudo-Static Analyses

- k = pseudo-static coefficient, constant that represents earthquake loading
- k is usually calculated as a fraction of peak ground acceleration (PGA)
- Pseudo-static analyses can be used with infinite slope, limit equilibrium (Ordinary method of slices, Morgenstern-Price, Modified Bishop, Spencer, etc.) or finite element analyses



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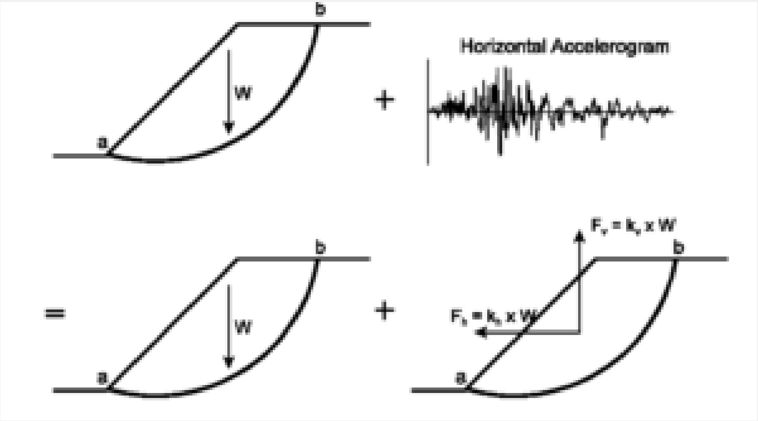
Pseudo-Static Analyses

- Advantages
  - Usually conservative
  - Can also add a vertical downward component
  - Much easier and faster than full dynamic analyses
- Disadvantages
  - Does not take duration or frequency content of ground motion into account
  - Does not take cyclic loading into account
  - Only provides factor of safety (no strains or displacements)

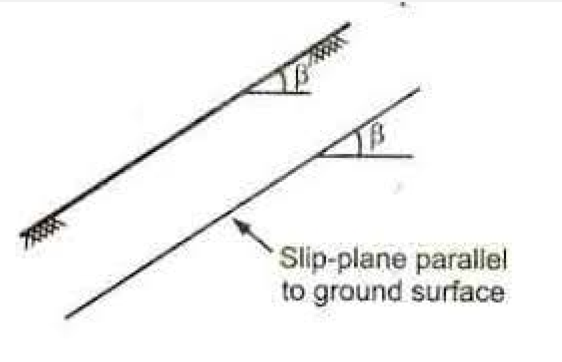


Pseudo-Static Analyses: Infinite Slope

- Pseudo-static equation for fully saturated infinite slope:

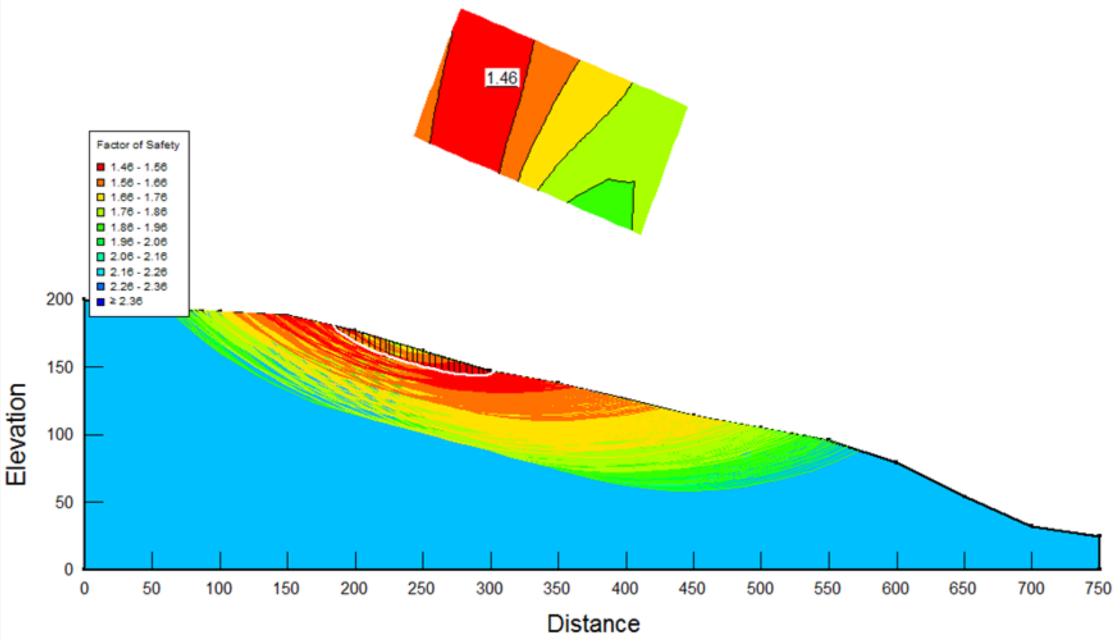
$$FS = \frac{s_u}{\sigma'_v * cos\vartheta * sin\vartheta + \sigma_v * k_H * cos^2\vartheta}$$

- Main assumptions:
  1. The thickness of the failing soil mass is much less than the length of the slope
  2. The failure plane is parallel to the surface
  3. The failing soil mass acts as a rigid block



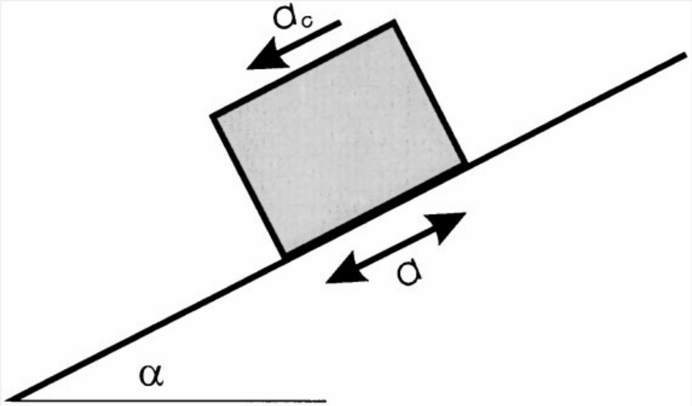
Pseudo-Static Analyses: Limit Equilibrium

- Pseudo-static analysis same as static except add horizontal inertial load F = k*W where W is weight of the failing soil mass

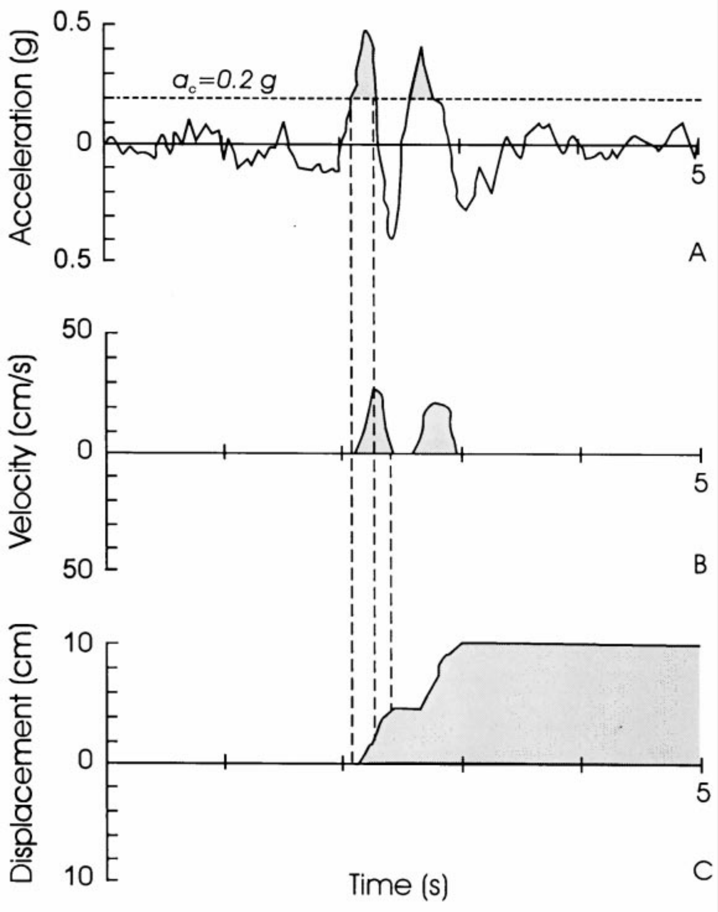


Displacement Based: Newmark Sliding Block

- Landslide modelled as rigid block resting on sliding plane
- a_c (k_y) is the critical yield acceleration to overcome shear resistance and initiate sliding
- k_y can be estimated as the value of k_H when pseudo-static FS = 1
- Accelerations above k_y are double integrated to calculate displacement



Jibson 2000



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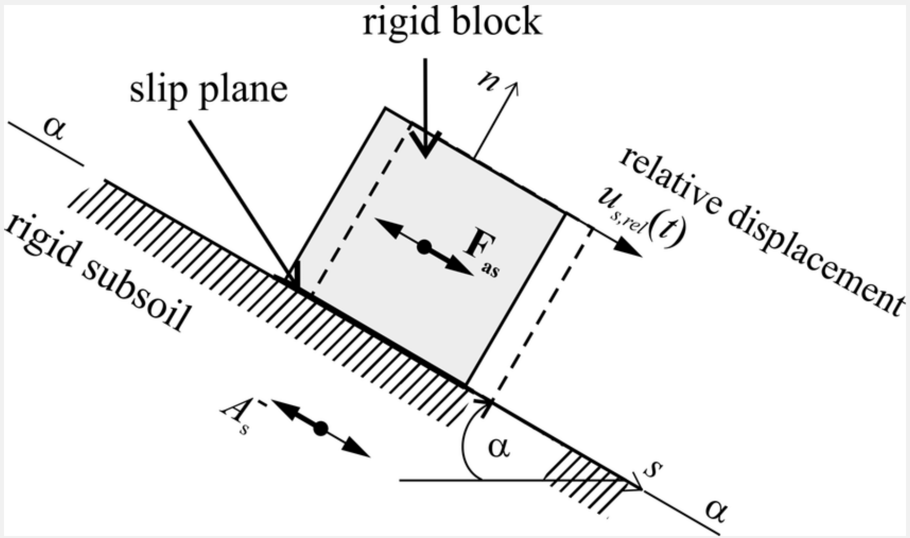
Displacement Based: Newmark Sliding Block

- Advantages
  - Provides displacements
  - Takes duration into account
  - Fast
- Disadvantages
  - k_y difficult to calculate, no physical meaning
  - Assumes soil acts as a rigid block, neglects dynamic response of soil
  - Does not take cyclic loading into account
  - Linear failure plane



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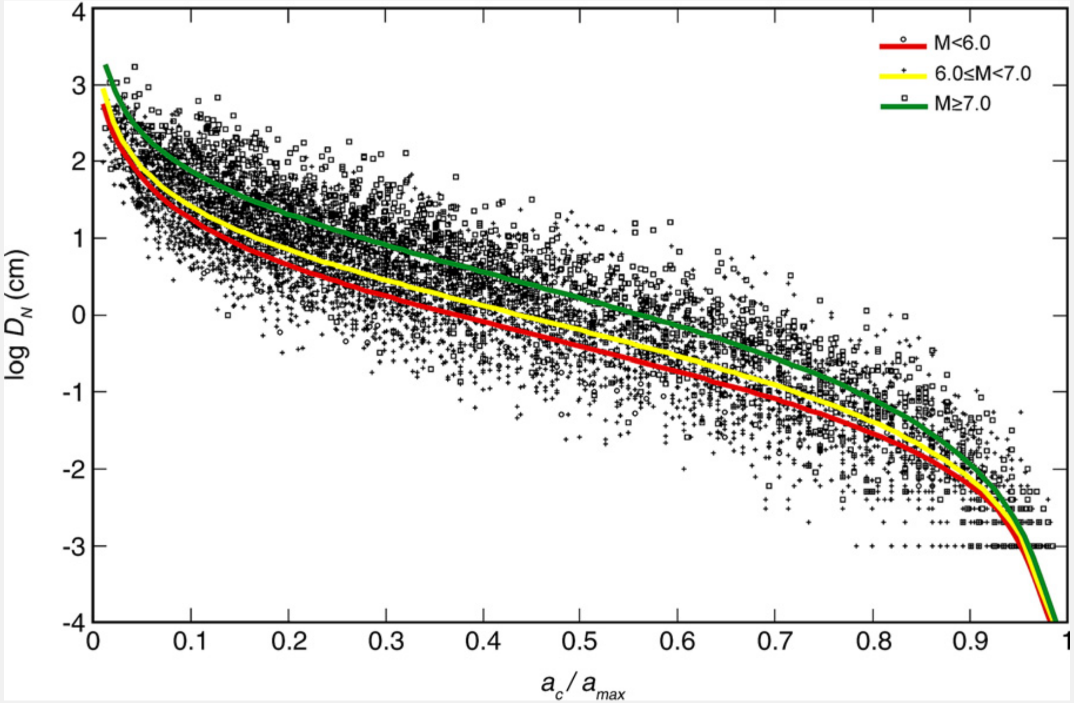
Displacement Based: Simplified Methods

- Two common methods based on Newmark sliding block analyses:
  - Jibson (2007)
  - Saygili and Rathje (2008)
- Inputs: k_y, M_w, and PGA
- Easy to implement on a regional basis
- k_y can be taken as value when pseudo-static FS = 1



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Jibson 2007

Displacement Based: Simplified Methods

Saygili and Rathje (2008)

$$ln(D) = 4.89 - 4.85 * \left(\frac{k_y}{PGA}\right) - 19.64 * \left(\frac{k_y}{PGA}\right)^2 + 42.49 * \left(\frac{k_y}{PGA}\right)^3$$
$$-29.06 * \left(\frac{k_y}{PGA}\right)^4 + 0.72 * ln(PGA) + 0.89 * (M_w - 6)$$

Jibson (2007)

$$log(D) = -2.710 + log\left[\left(1 - \frac{k_y}{PGA}\right)^{2.335} * \left(\frac{k_y}{PGA}\right)^{-1.478}\right] + 0.424 * M_w$$

D in cm, PGA and k_y in g, M_w = moment magnitude

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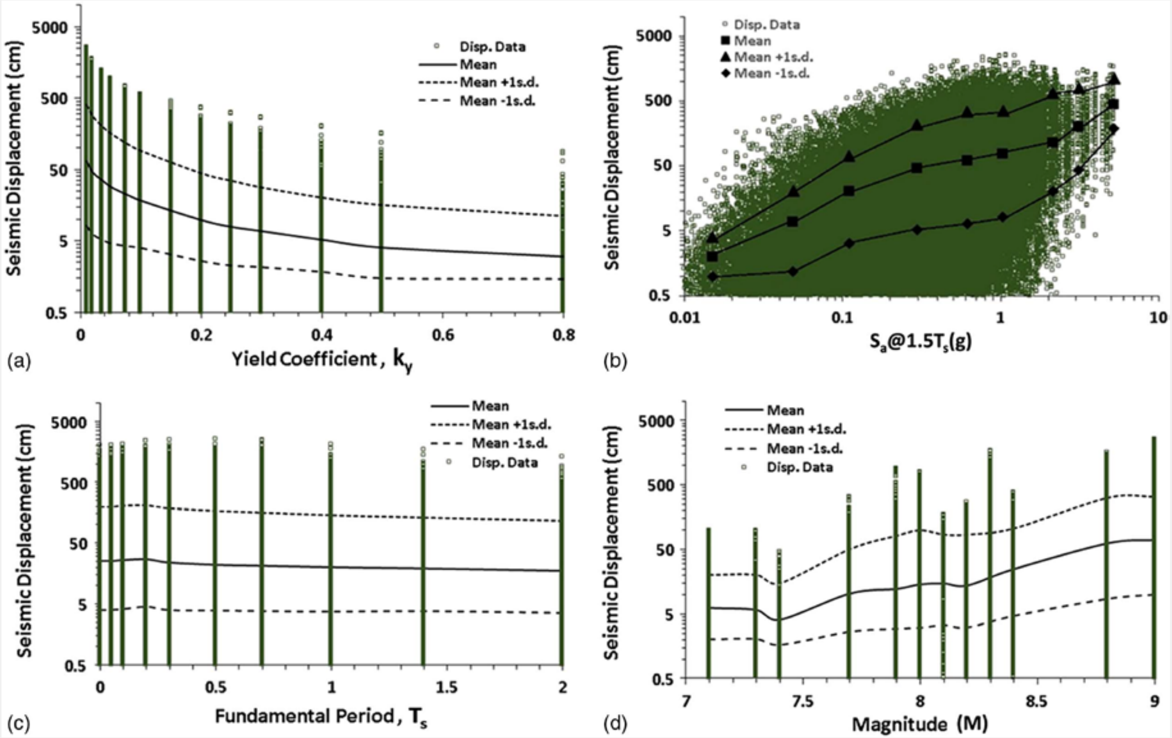
Displacement Based: Simplified Methods

- Models based on a fully coupled stick slip model:
  - Bray and Travasarou (2007)
  - Bray et al (2018)
- Inputs: k_y, M_w, Ts, and Sa at T = 1.5∗Ts
- Simplified models have large scatter



Bray et al 2018

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Displacement Based: Simplified Methods

Ts > 0.05

$$\ln(D) = -1.10 - 2.83\ln(k_y) - 0.333(\ln(k_y))^2 + 0.566\ln(k_y)\ln(S_a(1.5T_s)) + 3.04\ln(S_a(1.5T_s)) - 0.244(\ln(S_a(1.5T_s)))^2 + 1.50T_s + 0.278(M-7)$$

Ts = 0

$$\ln(D) = -0.22 - 2.83\ln(k_y) - 0.333(\ln(k_y))^2 + 0.566\ln(k_y)\ln(\mathrm{PGA}) + 3.04\ln(\mathrm{PGA}) - 0.244(\ln(\mathrm{PGA}))^2 + 0.278(M-7) \pm \varepsilon$$

level ground

$$Ts = \frac{4 * H}{Vs}$$

sloping ground

$$Ts = \frac{2.6 * H}{Vs}$$

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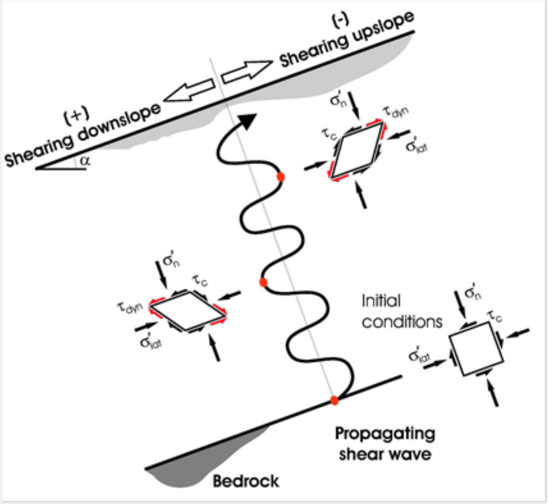
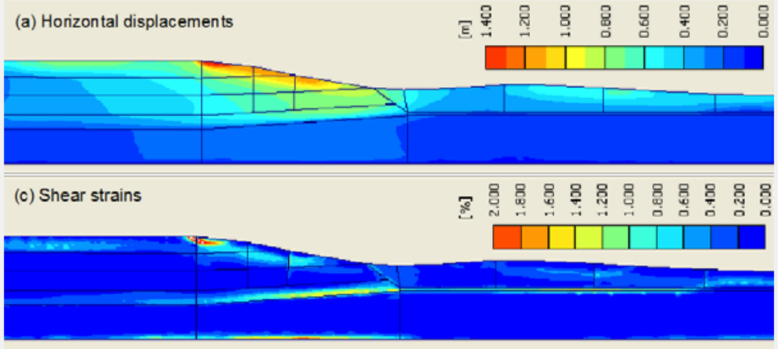
Bray and Travasarou (2007)

Nonlinear Dynamic Analyses

- Advantages
  - Can accommodate complex soil constitutive models
  - The failure plane is not predefined
  - The full ground motion is used to define the earthquake
- Disadvantages
  - Time consuming
  - Requires lots of information regarding the soil and ground motion
- Common programs
  - 1D (NGI in house programs AMPLE, QUIVER)
  - 2D/3D (PLAXIS, FLAC, ABAQUS)





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Eurocode 8 Guidelines

- No analysis is necessary for structures with importance class = 1 and if it is known from comparable experience that the ground at the construction site is stable.
- Topographic effects should be taken into account for structures with importance class > I
- Acceptable methodologies are finite element or rigid block analyses. Pseudo-static analyses may also be used if:
  - Surface topography and soil stratigraphy do not contain very abrupt irregularities
  - No liquefiable soils or sensitive clays (quick clays)

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1998-5

November 2004

ICS 91.120.25

Supersedes ENV 1998-5:1994

English version

Eurocode 8: Design of structures for earthquake resistance Part 5: Foundations, retaining structures and geotechnical aspects

Eurocode 8: Calcul des structures pour leur résistance aux séismes Partie 5: Fondations, ouvrages de soutènement et aspects géotechniques

Eurocode 8: Auslegung von Bauwerken gegen Erdbeben Teil 5: Gründungen, Stützbauwerke und geotechnische Aspekte

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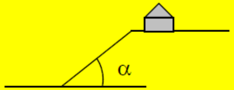
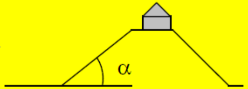
Eurocode 8 Guidelines: Pseudo-static Coefficient

$$k_H = 0.5 * \gamma_I * a_{gR} * S * ST = 0.5 * PGA * ST \qquad k_V = 0.33 * k_H$$

Topographic amplification factors (ST)

Type of topographic profile	Sketch	Average slope angle, α	ST
Isolated cliff and slope		> 15°	1.2
Ridge with crest width significantly less than base width		15° to 30°	1.2
		> 30°	1.4

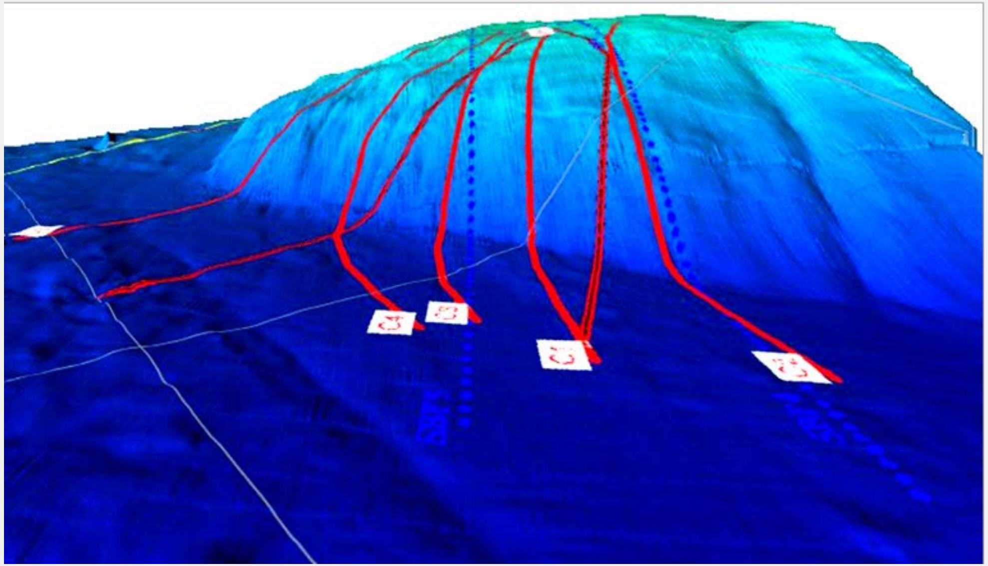
- k_H = horizontal pseudo-static coefficient
- k_V = vertical pseudo-static coefficient
- γ_I = importance factor
- a_{gR} = reference peak ground acceleration on rock (Type A)
- S = soil amplification factor
- ST = topographic amplification factor

Eurocode 8 Guidelines: Material Parameters

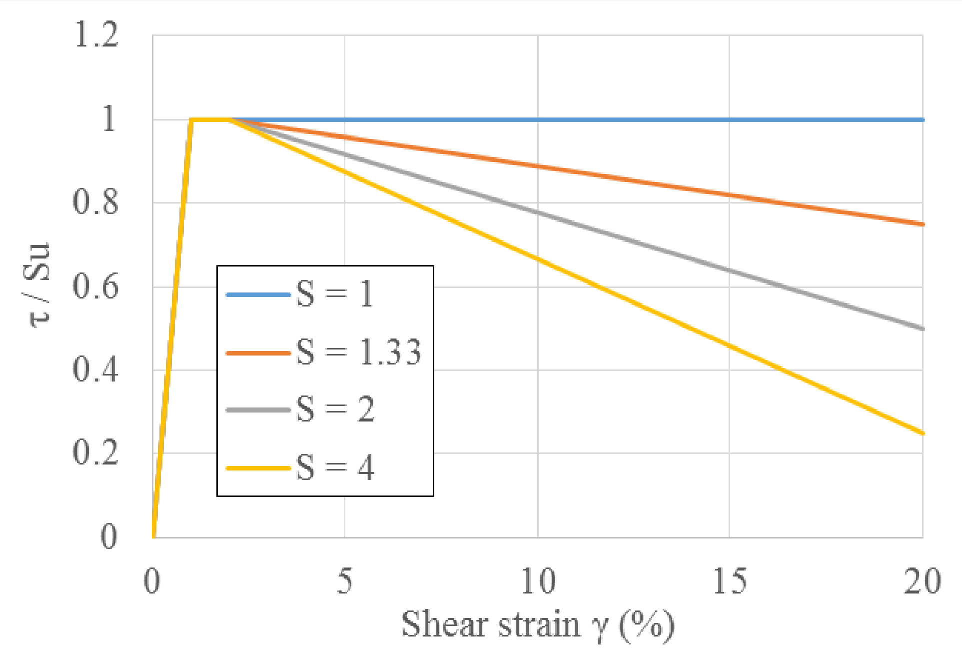
- Partial factors (γ_M) for strength values in Norway are:
  - Clay (γ_{cu}) = 1.1
  - Quick clay (γ_{cu}) = 1.2
  - Sand ($\gamma_{\tau cu}$ and γ_ϕ) = 1.1
  - Cohesionless fills ($\gamma_{\tau cu}$ and γ_ϕ) = 1.2
- If no material factors are used, these are equivalent to minimum acceptable factors of safety

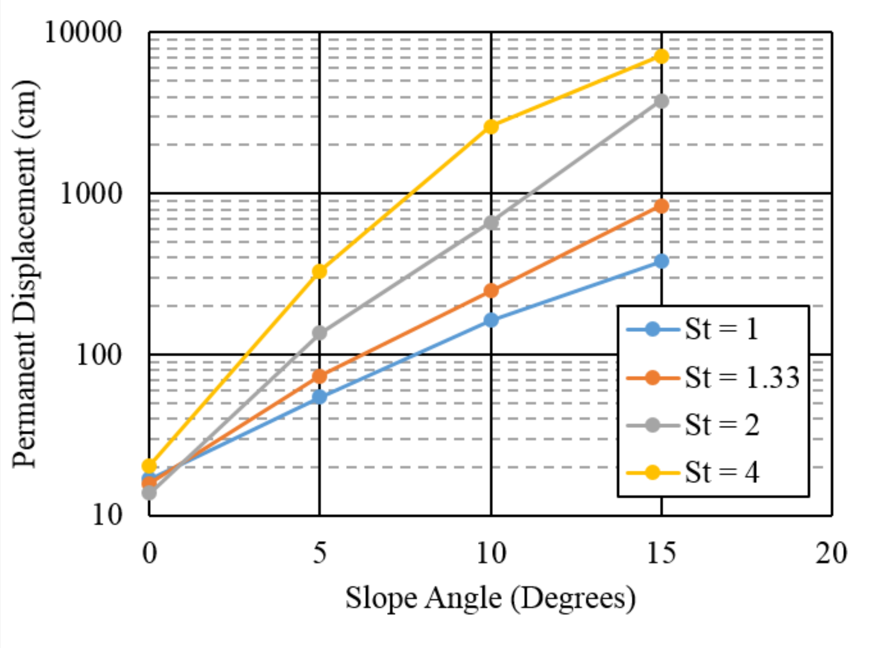
Important Considerations

- Strain softening
- Liquefaction
- Multi-directional shaking
- 3D geometry
- Retrogressive sliding



Important Considerations: Strain Softening

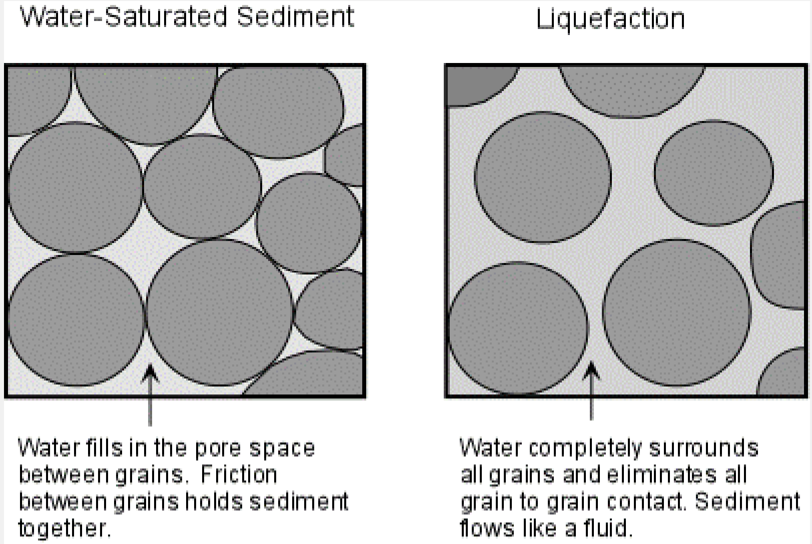




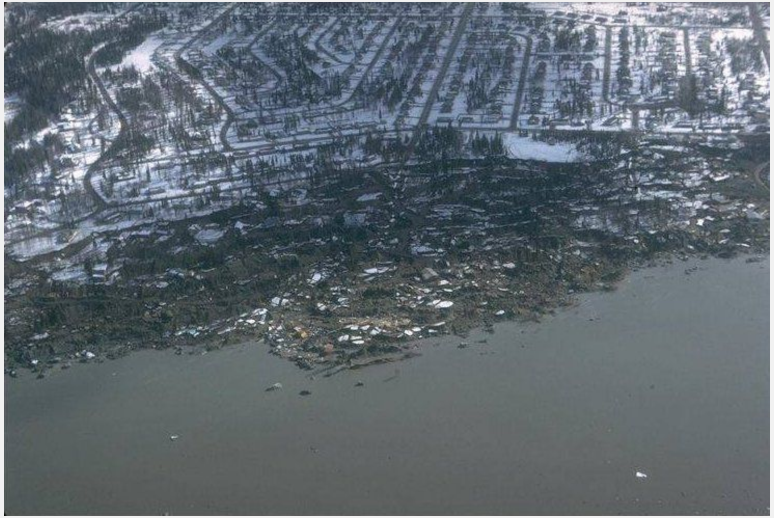
Carlton et al. (2016)

Important Considerations: Liquefaction

- Liquefaction is the transformation of a granular material from a solid to a liquefied state as a consequence of increased pore-water pressure (u) and reduced effective stress (σ'_v).



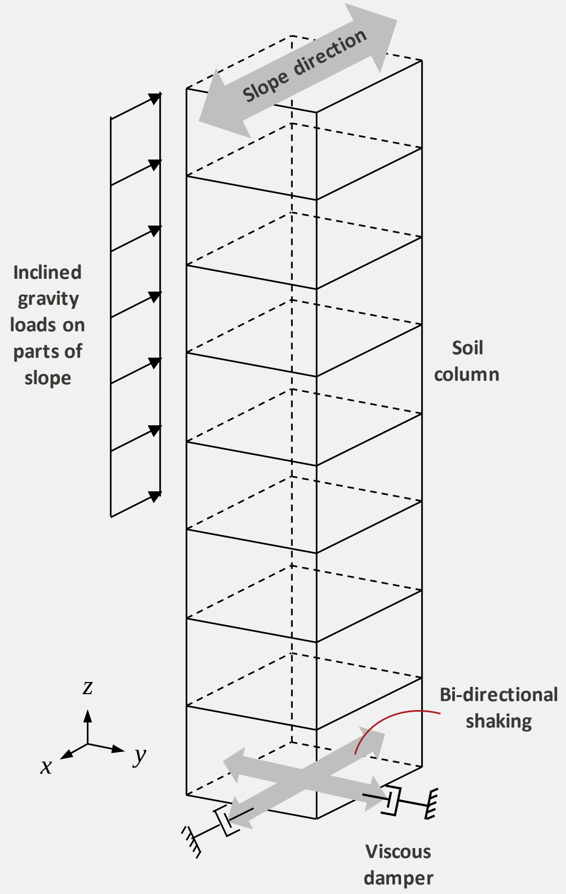
$$\sigma'_v = \sigma_v - u$$



Turnagain Heights Slide, Alaska, 1964 (Seed and Wilson, 1967)

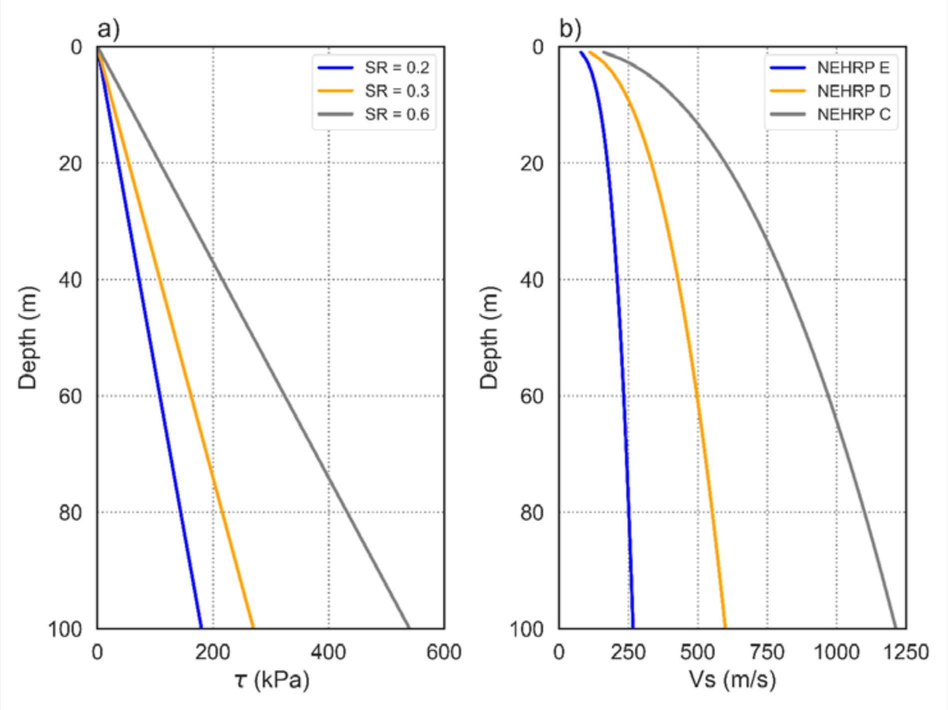
Important Considerations: Multidirectional Shaking

- Seismic slope-stability analyses almost always consider only one component of ground motion (in slope direction)
- Earthquakes are 3D phenomena
- Performed 28,100 3D finite element analyses in OpenSees to estimate effect of multidirectional shaking on slope stability

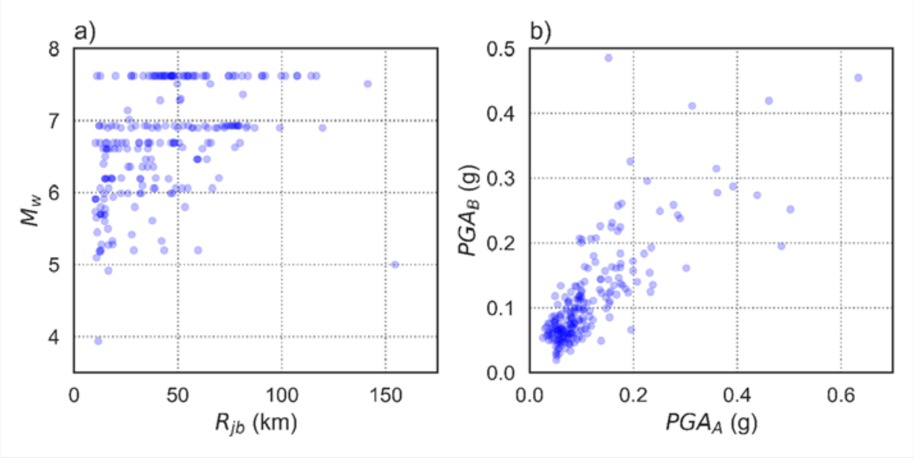


Løkke and Carlton (2022)

Important Considerations: Multidirectional Shaking



- 48 soil profiles combinations
  - 3 slope angles, 2 slope heights, 3 soil strengths, 3 soil stiffnesses
- 230 ground motion record pairs
- 4 combinations of ground motion orientation



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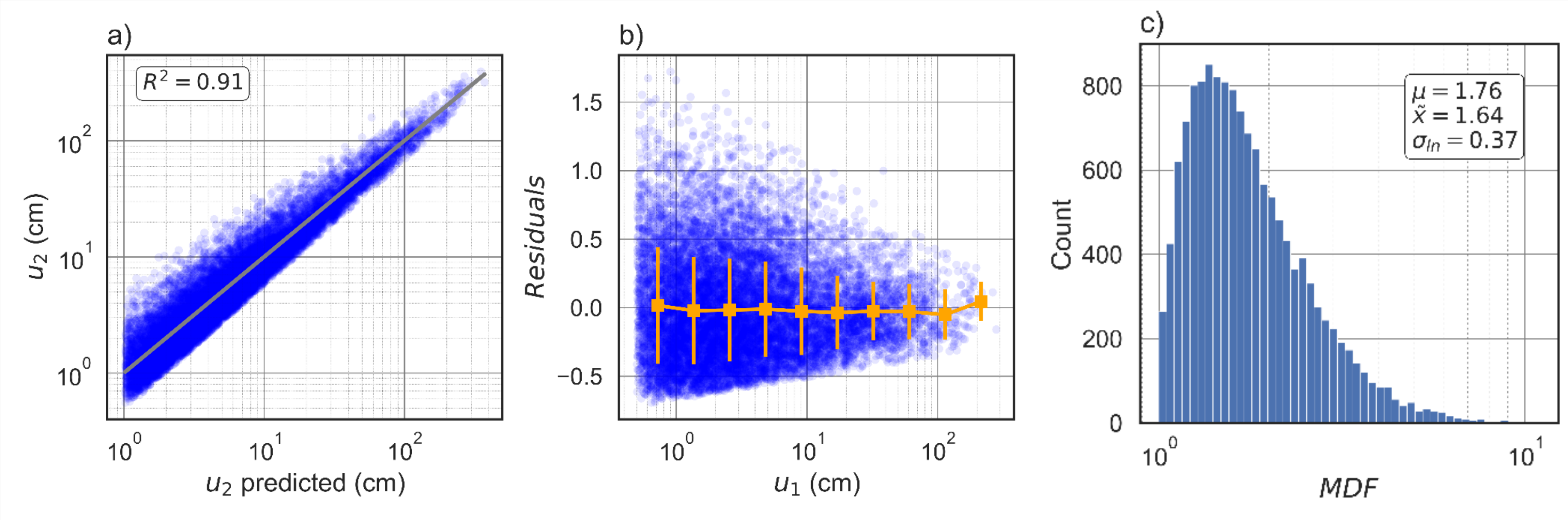
Løkke and Carlton (2022)

Important Considerations: Multidirectional Shaking



$$ln(u_2) = 0.923 * ln(u_1) + 0.663$$

$$\sigma_{ln} = -0.051 * ln(u_1) + 0.415$$

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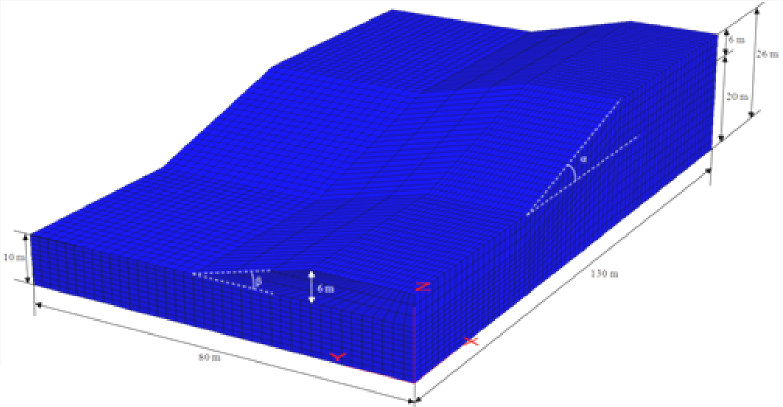
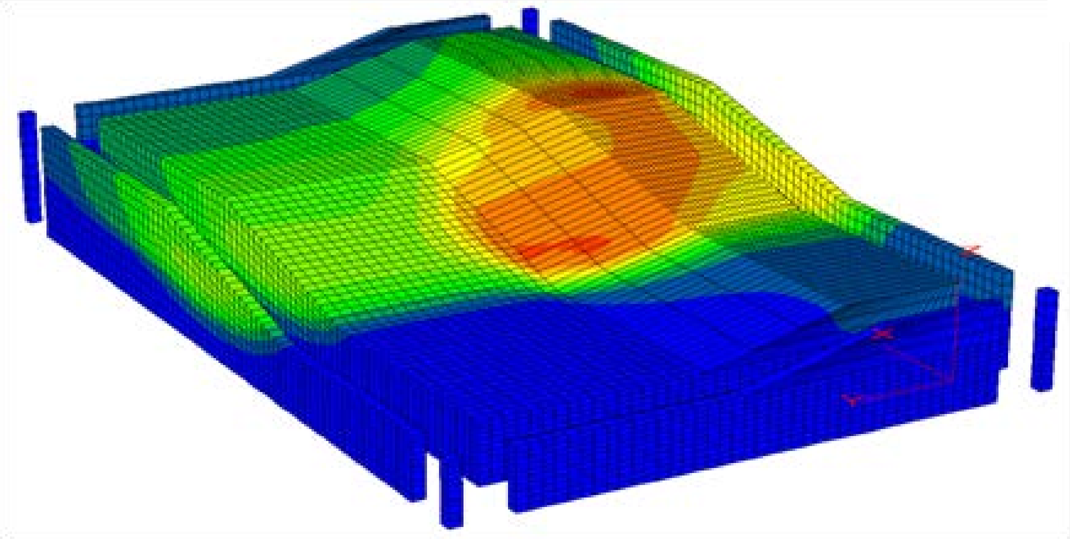
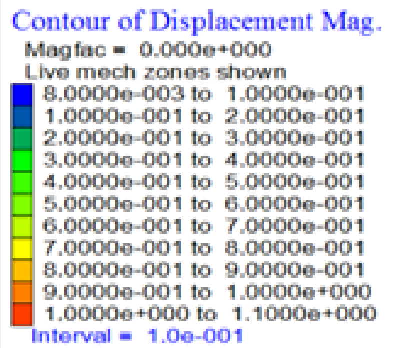
Løkke and Carlton (2022)

Important Considerations: 3D Geometry

Earthquake response of 3D slope due to shaking in one direction - Example results: displacement contours for 10 cycles of sine wave, frequency = 2 Hz, peak acceleration = 0.15g, and $\alpha = \beta = 1:4$



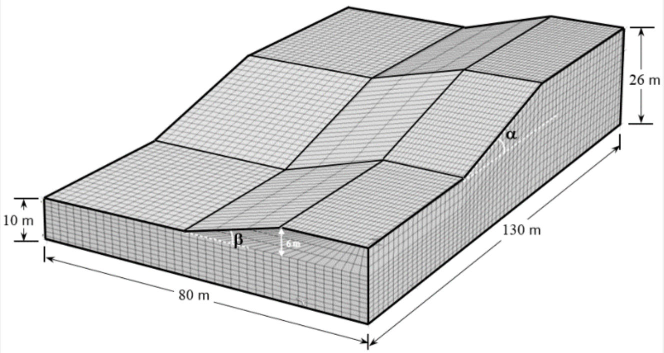


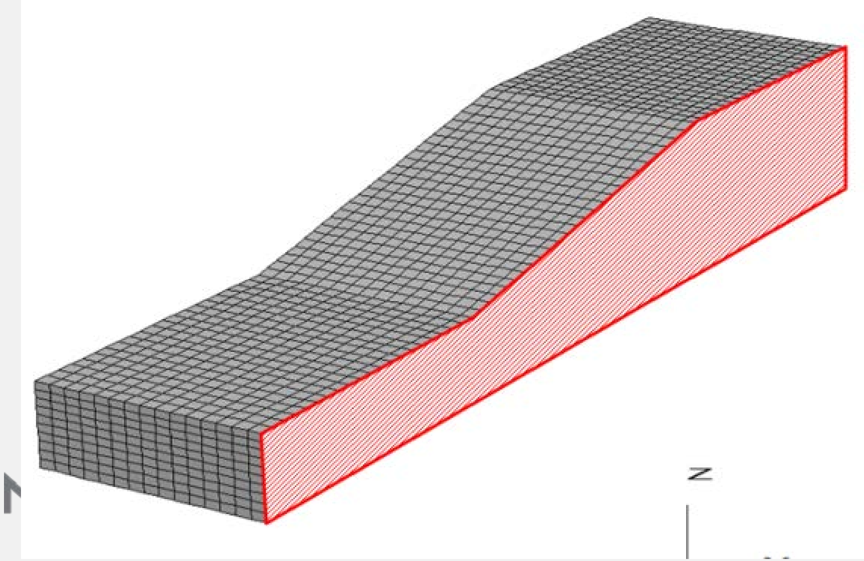


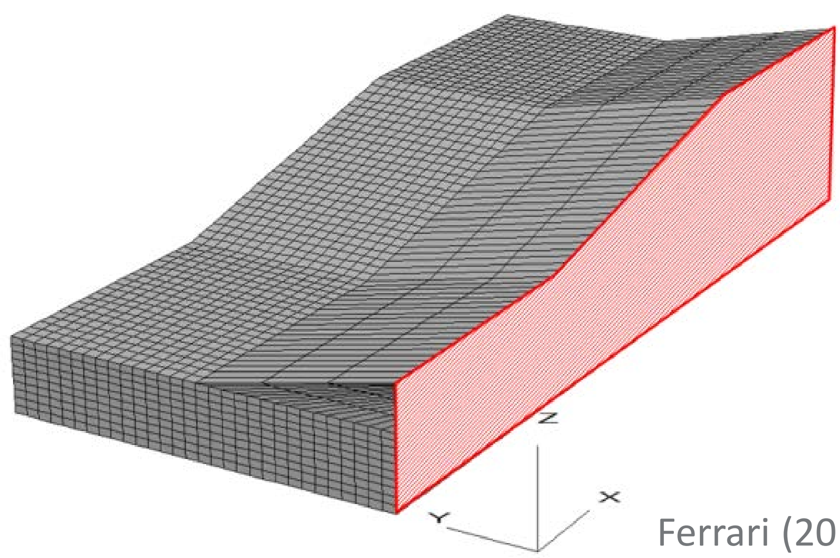
Ferrari (2012)

Important Considerations: 3D Geometry

Effect of 3rd Dimension – Stresses and strains on 2-D sections across slope



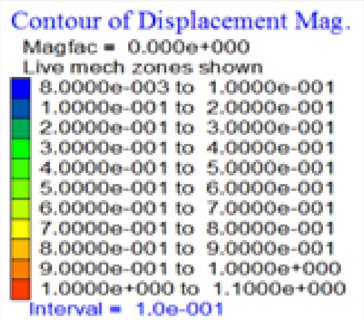




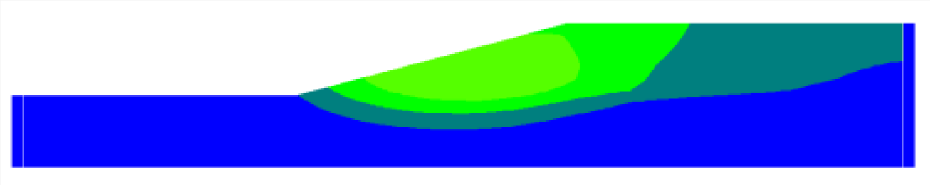
Ferrari (2012)

Important Considerations: 3D Geometry

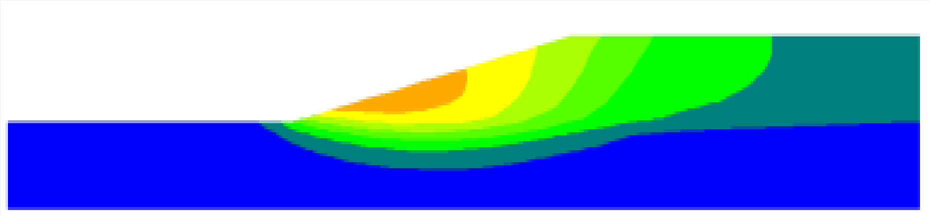
Effect of 3rd Dimension:
Response of 2-D sections across slope



Shallow sections

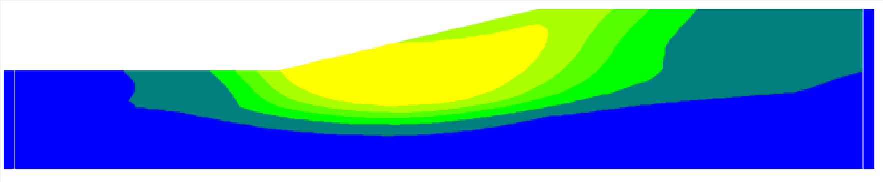


2-D model

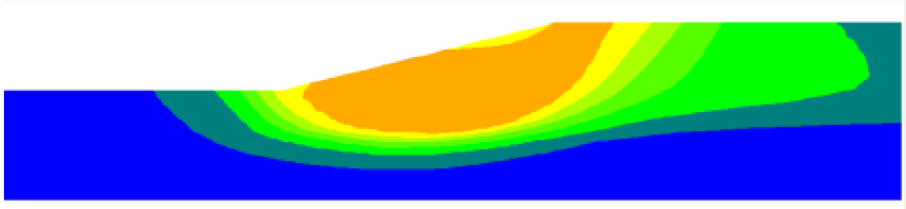


3-D

Deep sections



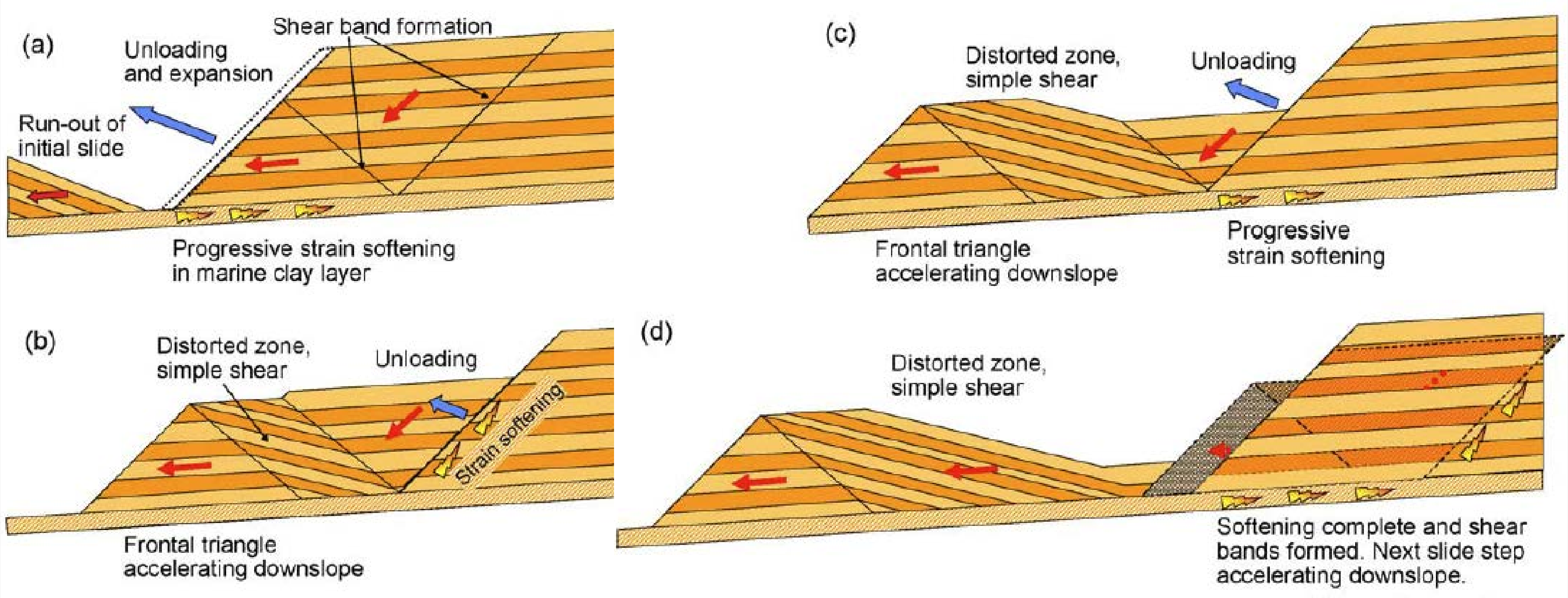
2-D model



3-D

Ferrari (2012)

Important Considerations: Retrogressive sliding



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Kvalstad et al. (2005)