

Stability of Natural and Man-made Slopes: from FS to RFEM and MPM

Nejan HUVAJ

METU Civil Engineering Department, Ankara, Turkey
nejan@metu.edu.tr



PROCEEDINGS
OF THE
1st
INTERNATIONAL CONFERENCE
ON
SOIL MECHANICS AND
FOUNDATION ENGINEERING
JUNE 22 to 26, 1936

VOLUME I

GRADUATE SCHOOL OF ENGINEERING
HARVARD UNIVERSITY
CAMBRIDGE, MASS.

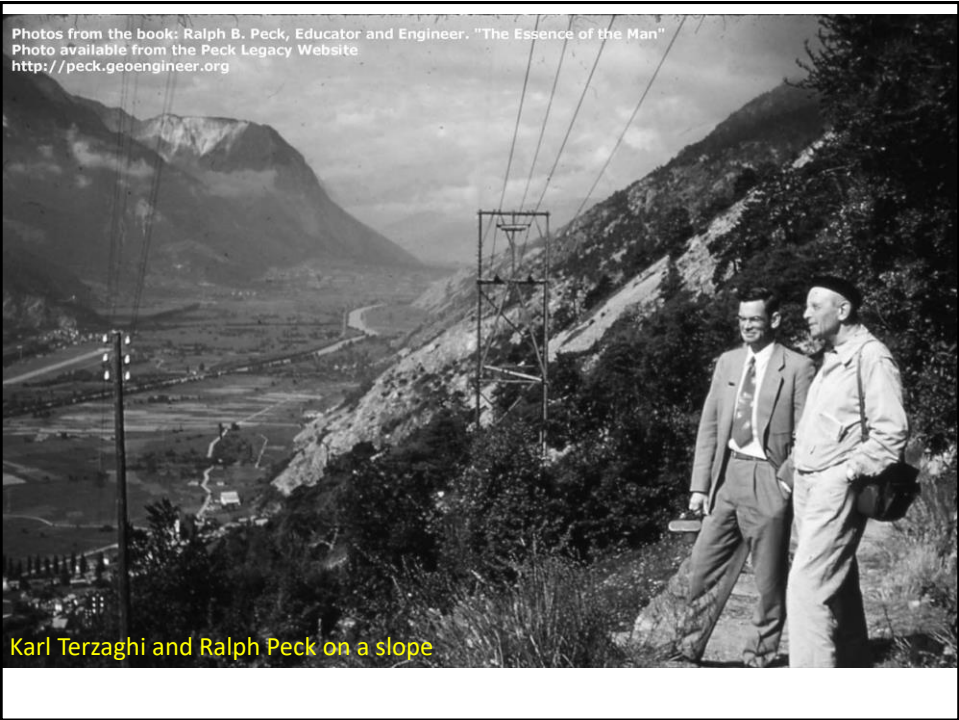
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SECOND PRINTING



Stability of Slopes has
been a topic of interest
for many years...

PROCEEDINGS OF THE 1st INTERNATIONAL CONFERENCE ON SOIL MECHANICS AND FOUNDATION ENGINEERING JUNE 22 to 26, 1936		
Section G: STABILITY OF EARTH AND FOUNDATION WORKS AND OF NATURAL SLOPES		
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Fourth Rankine Lecture 4th Rankine Lecture, 1964**LONG-TERM STABILITY OF CLAY SLOPES**

by

A. W. SKEMPTON, D.Sc., M.I.C.E., F.R.S.*

I wish to thank the British Geotechnical Society for inviting me to give the fourth Rankine Lecture, and to thank Dr Cooling for his very kind remarks.

In preparing the Lecture I have received a great deal of help from various people, especially Mr John Hutchinson, Dr Laurits Bjerrum and Mr Kenneth Early, while most of the field work which I shall describe was carried out jointly with Dr David Henkel. The long-term stability of clay slopes has indeed been one of the preoccupations of Dr Henkel and myself for the past 12 years; and I would like to take this opportunity of paying tribute to the value of the contributions which he made in this particular subject, and generally to soil mechanics and engineering geology, during the time he spent in Great Britain. I am also deeply grateful to my wife for her interest, criticism, and suggestions which have been most valuable.

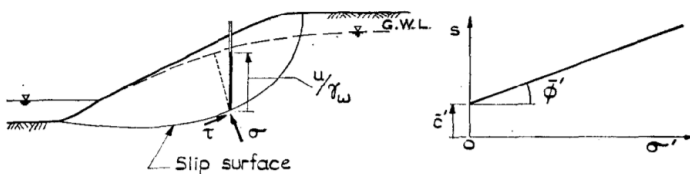
* Professor of Civil Engineering, Imperial College, University of London.

**Fourth Rankine Lecture 4th Rankine Lecture, 1964****LONG-TERM STABILITY OF CLAY SLOPES**

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τ = shear stress

σ = total pressure

u = pore pressure

$\sigma' = \sigma - u$ = effective pressure

In a stable slope

$$\sum \tau = \sum \bar{c}' + \sum (\sigma - u) \frac{\tan \bar{\phi}'}{F} \quad F = \text{factor of safety}$$

When a slip occurs $F = 1.0$ and $\sum \tau = \sum s$

LONG - TERM STABILITY OF CLAY SLOPES

39th Rankine Lecture, 1999Leroueil, S. (2001). *Géotechnique* 51, No. 3, 197–243**Natural slopes and cuts: movement and failure mechanisms**

S. LEROUÉIL*

Movements and failure of cuts and natural slopes constitute an important geotechnical problem that involves a variety of geomaterials in a variety of geological and climatic contexts, and which has a major socio-economic impact in many countries. The paper reviews the state of knowledge in this domain, examining the basic aspects of soil mechanics that are relevant to the context of slopes, the importance of water on slope behaviour, and then the different stages of slope movements: pre-failure, failure, post-failure and reactivation.

Les mouvements et la rupture des tranchées et naturelles constituent un problème géotechnique qui demande une variété de géomatériaux dans de contextes géologiques et climatiques, ce qui impact socio-économique majeur dans bien des études fait le point sur l'état des connaissances dans ce domaine, examinant les aspects fondamentaux de la mécanique des sols dans le contexte des pentes, l'impact de l'eau sur le comportement de la pente et les différents stades des mouvements de terrain: pré-rupture, rupture, post-rupture et réactivation.

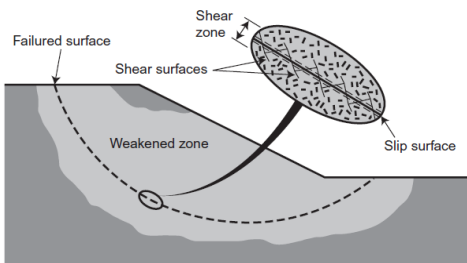


Fig. 59. Weakened zone, shear zone and slip surface in a slope

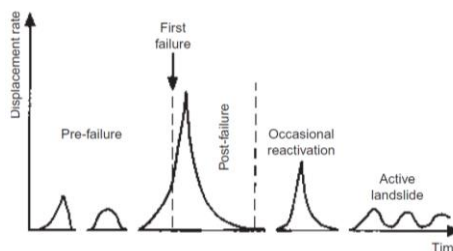


Fig. 2. Different stages of slope movements

55th Rankine Lecture, 2015**Hazard, Risk and Reliability in Geotechnical Practice**

by

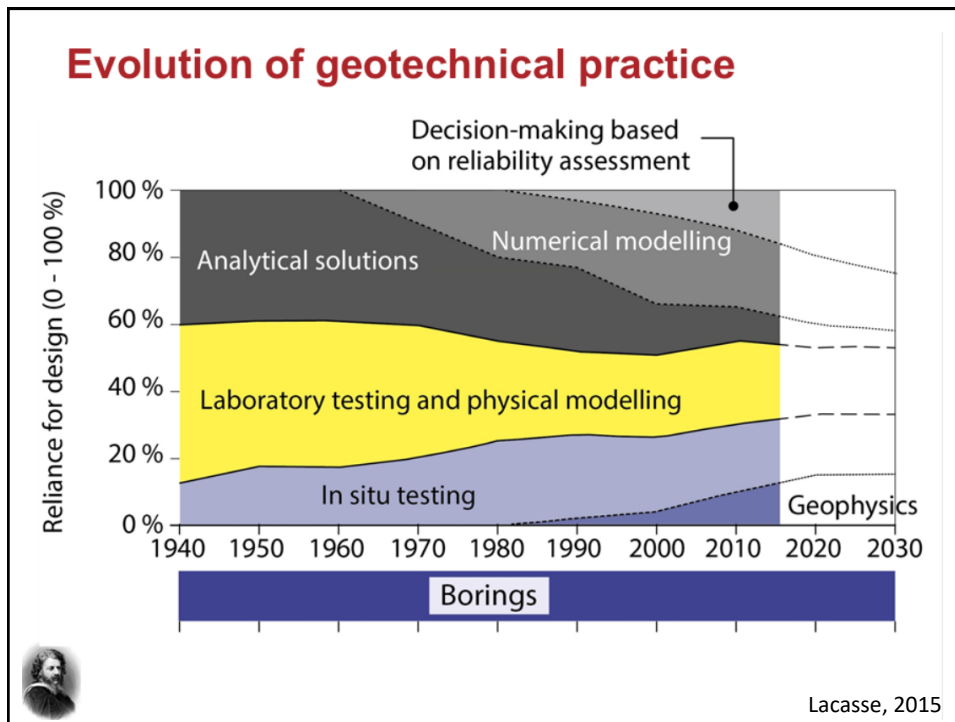
Suzanne Lacasse

Norwegian Geotechnical Institute

Oslo, Norway

**Contents of lecture**

1. Basic concepts and early work
2. Reliability analyses to ensure adequate safety and lead to cost-effective design-"Real-life" cases
 - Design of piles for offshore installations
 - Tresenda debris flow
 - Roşia Montaña tailings facility
 - New Orleans levees
- 3. Safety factor and definition of characteristic value**
4. Observational method and Bayesian updating
5. Challenges and emerging topics
6. Summary and conclusions



57th Rankine Lecture, 2017

57th Rankine Lecture

TRIGGERING AND MOTION OF LANDSLIDES



Eduardo E. Alonso
School of Civil Engineering
Universitat Politècnica de Catalunya, Barcelona, Spain



Contents

1. Creeping landslides
2. Fast landslides
3. Transition from creeping to fast motion
4. Continuum analysis. MPM
5. First time slides
6. THM analysis of landslides

Numerical Methods for Landslide analysis

Finite Element (FEM)
Finite Difference (FDM)
Arbitrary Lagrangian-Eulerian (ALE)
Coupled Eulerian-Lagrangian (CEL)
Material Point Method (MPM)
Smooth Particle Hydrodynamics (SPH)
Particle Finite Element Method (PFEM)
FEM + Lagrangian integration points (FEMLIP)
Element-free Galerkin (EFG)

MPM in landslide analysis

It is a continuum method. Constitutive equations

Incorporates FE methodologies

Statics + Dynamics + large deformations

Background mesh facilitates application of boundary conditions

Three-Phase MPM

The diagram illustrates the Three-Phase MPM approach. On the left, a grid of nodes is shown with a subdomain containing material points. A zoomed-in view on the right shows the interaction between gas, liquid, and solid phases. Labels include: subdomain, material point (p), computational mesh, node (i), gas, liquid, and solid.

Alonso, 2017

MPM

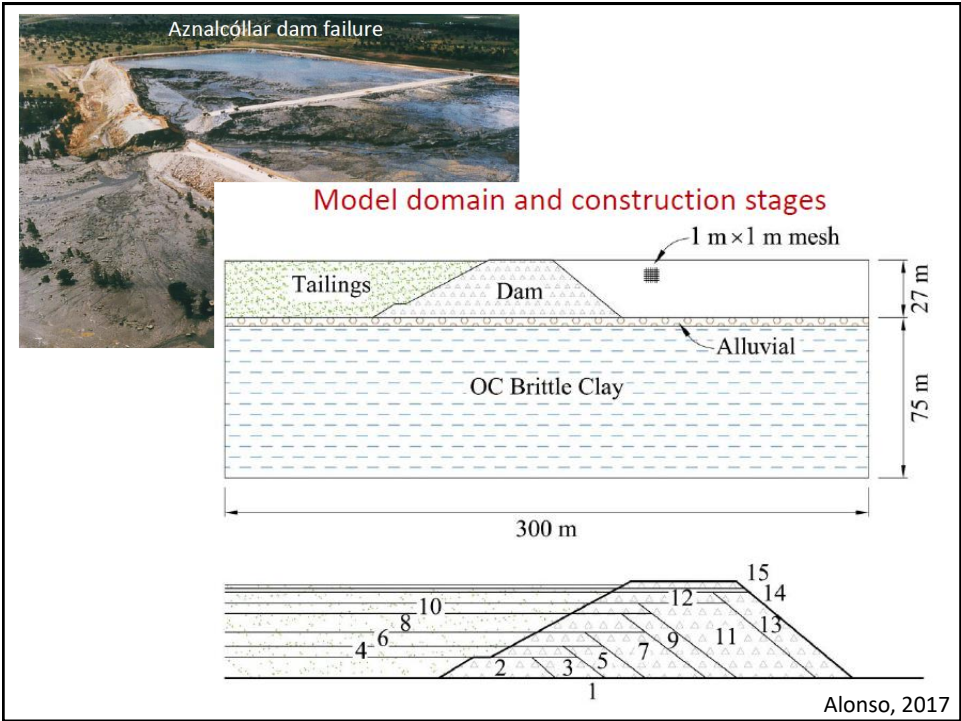
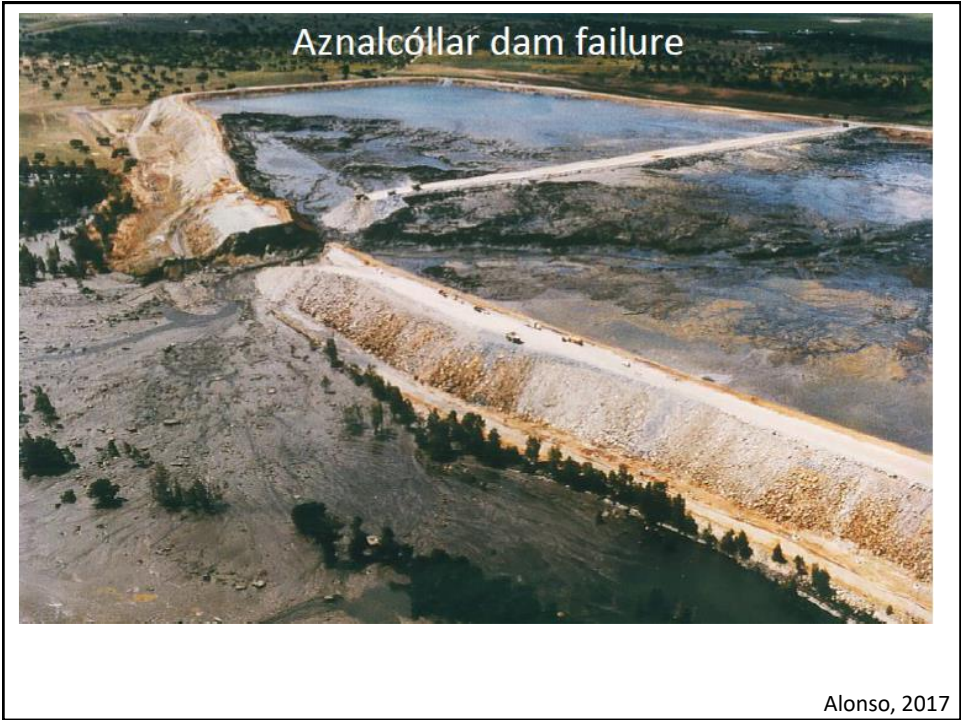
	One phase Dry	Two phases Saturated	Three phases Unsaturated
Single layer	 <i>Sulsky et al. (1994)</i>	 <i>Zabala & Alonso (2011)</i> <i>Jassim et al. (2013)</i>	 <i>Yerro et al. (2015)</i>
Multiple layer		 <i>Bandara (2013)</i> <i>Abe et al. (2014)</i>	 ?

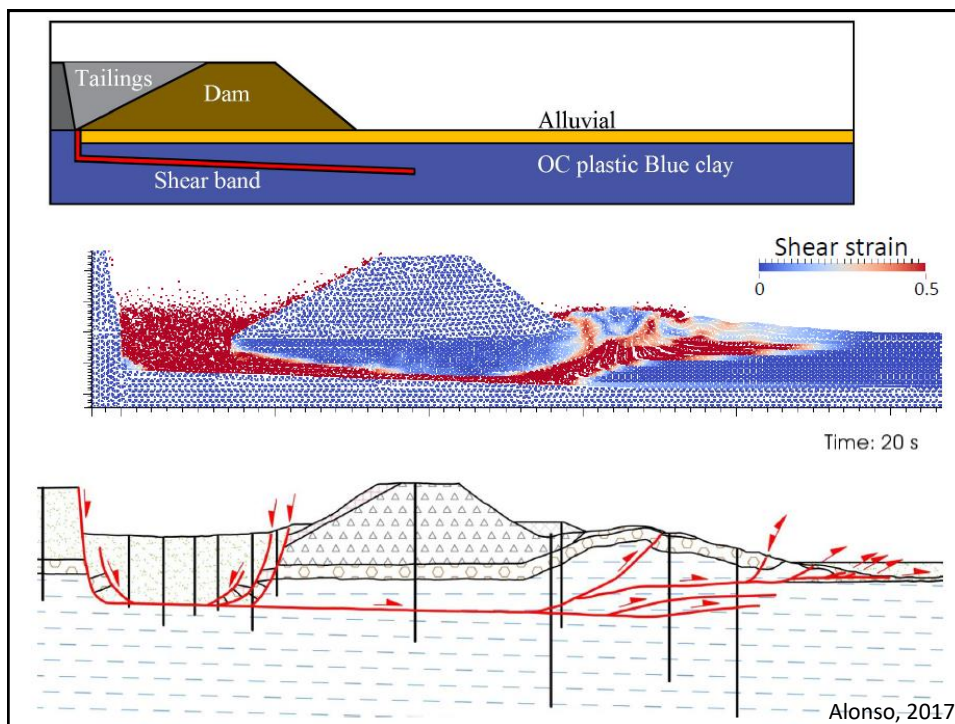
Solid

Liquid

Air

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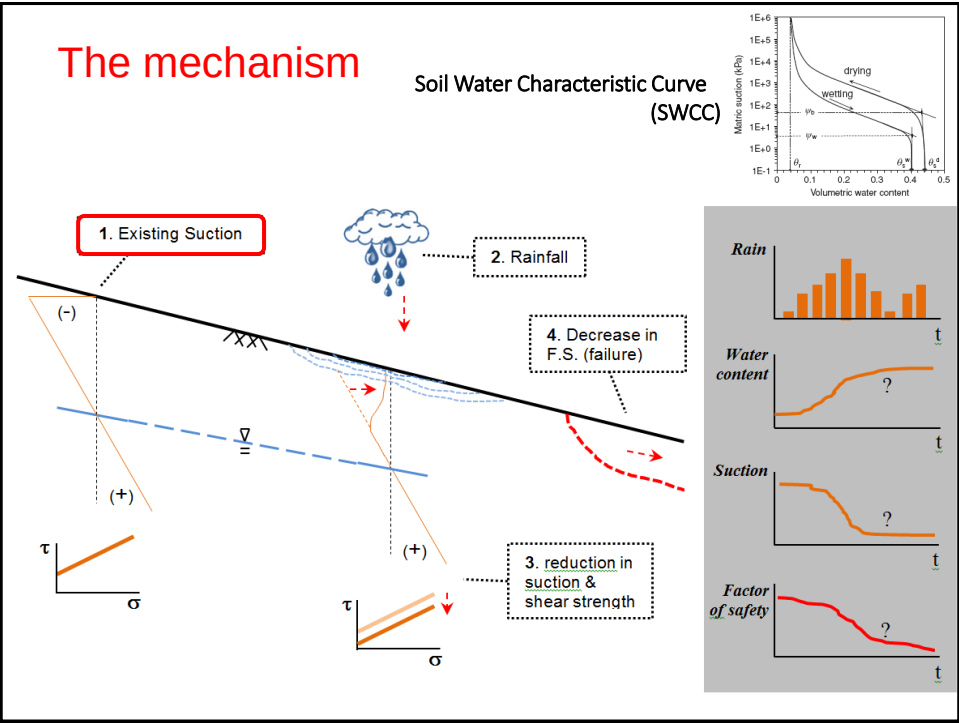
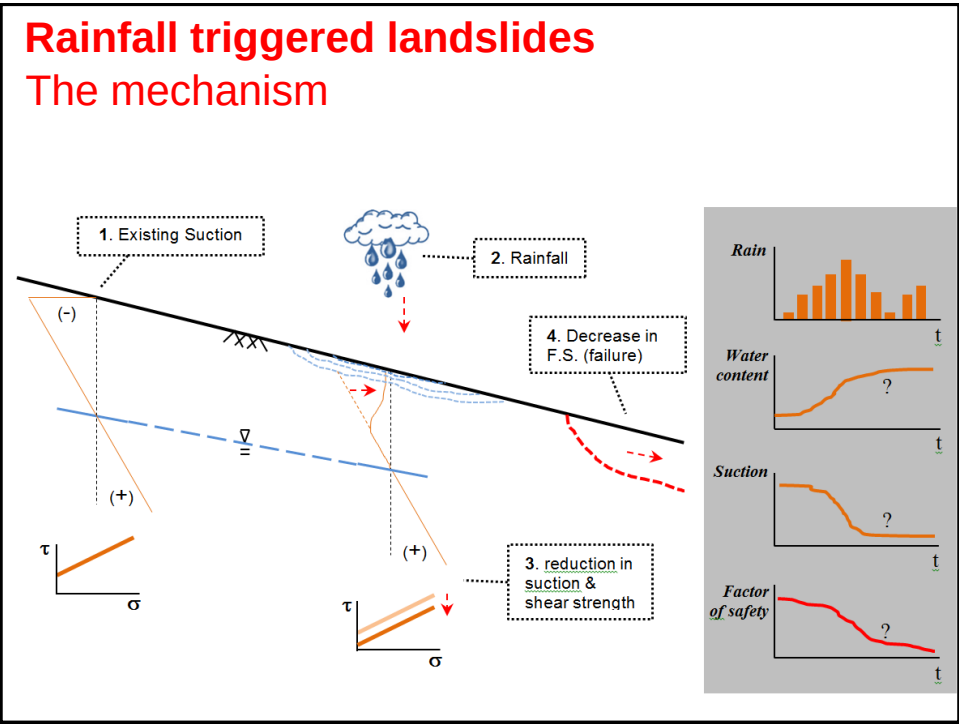


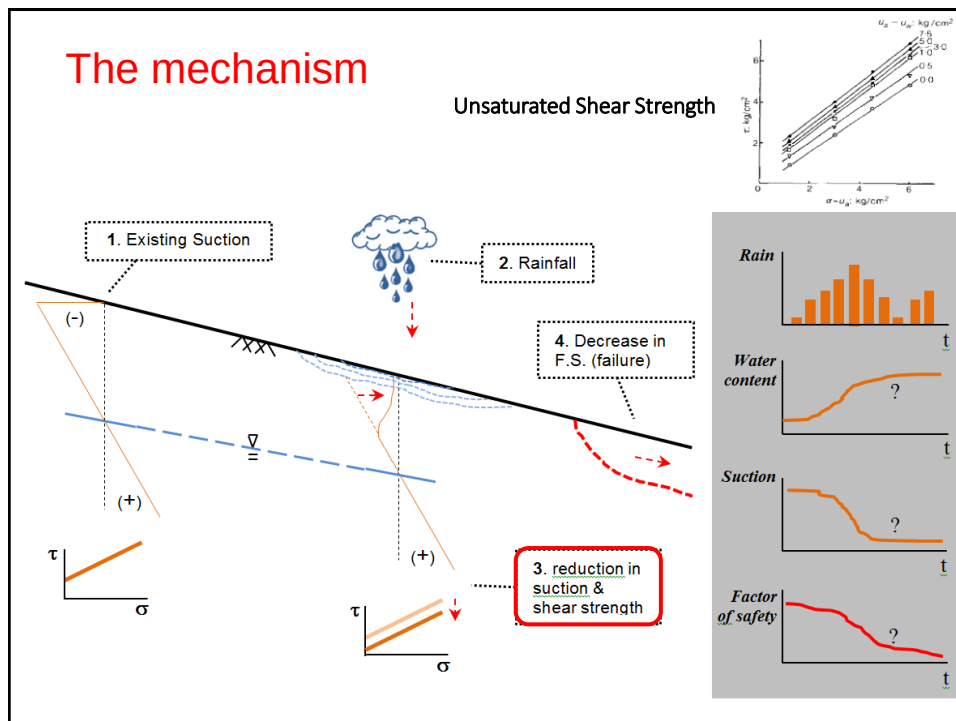


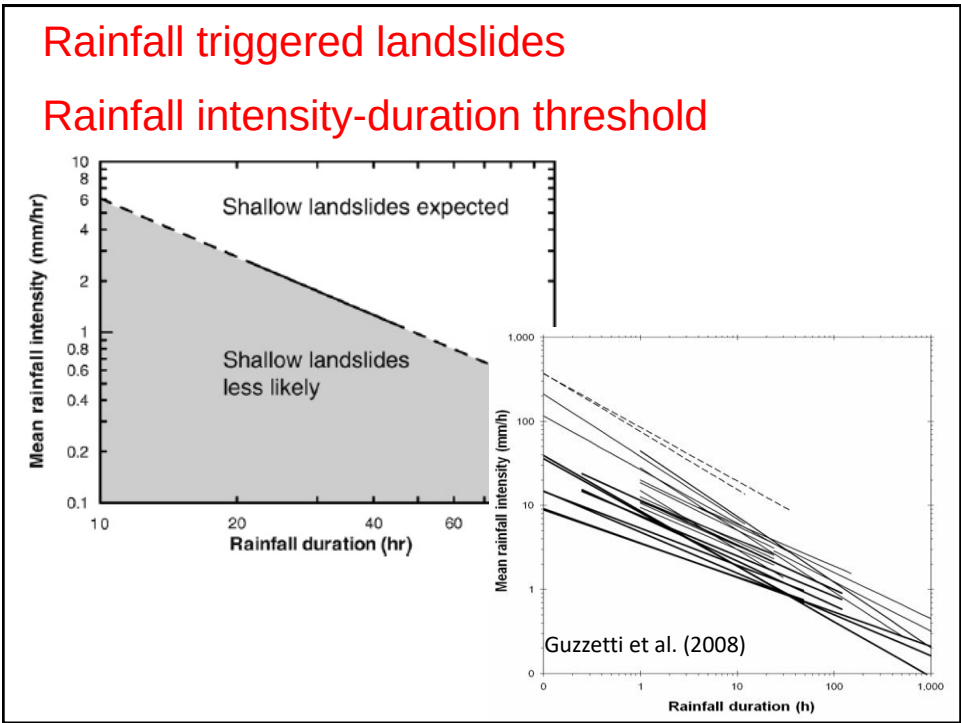
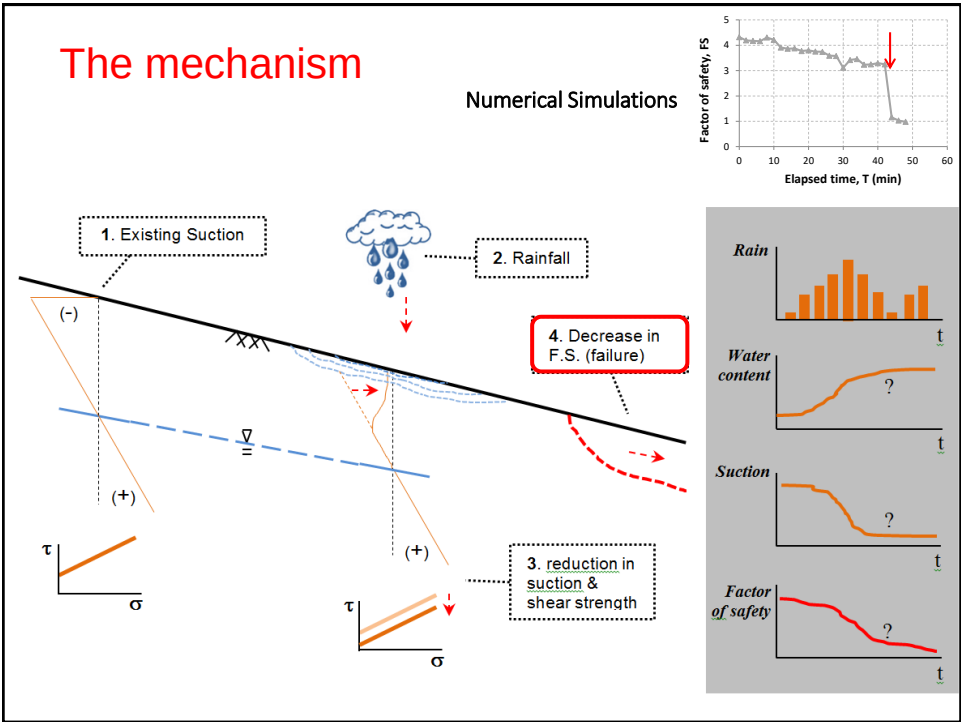
Advancing current knowledge

- **Well documented failure events**
- Geotechnical description before events
- Failure and post-failure observations
- Understanding
- Improved computational tools

Alonso, 2017

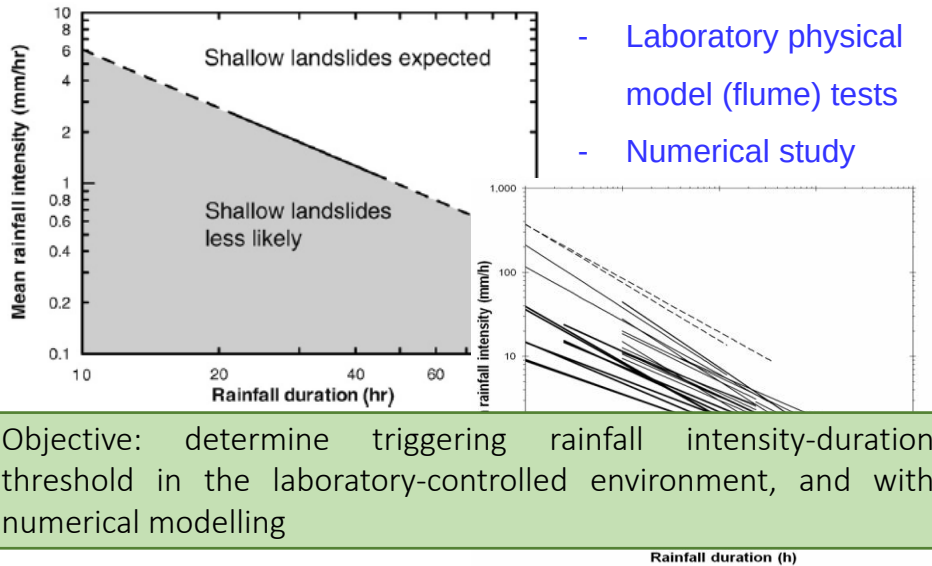






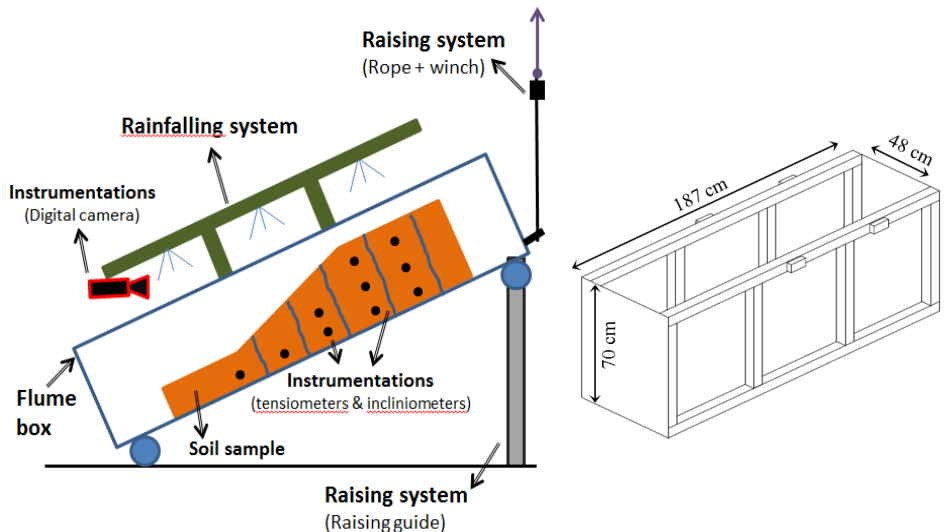
Rainfall triggered landslides

Rainfall intensity-duration threshold



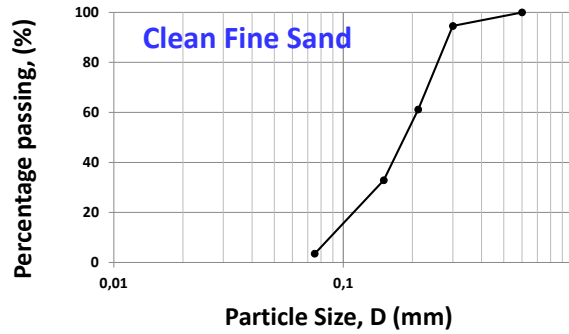
Laboratory physical model (flume) tests

A laboratory setup including a flume box, rainfall system and raising setup



Ahmadi-adli, Huvaj, Tokar (2017)

Laboratory physical model (flume) tests



D_{10} (mm) : 0.09

D_{30} (mm) : 0.14

D_{50} (mm) : 0.18

D_{60} (mm) : 0.202

C_c : 1.08

C_u : 2.24

Fines content (%): 3

USCS Soil Classification: SP

G_s : 2.663

$\gamma_{d \max}$: 1.648 g/cm³

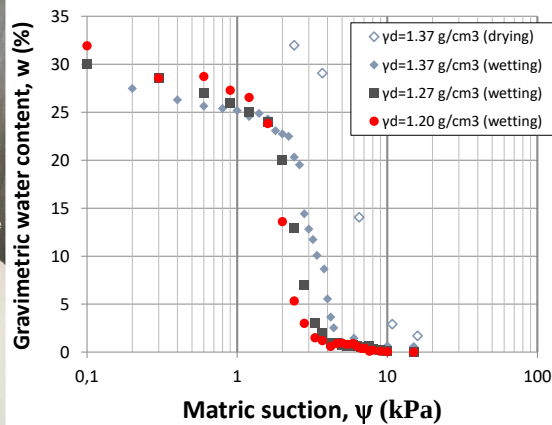
$\gamma_{d \min}$: 1.332 g/cm³

K_{sat} : 1.145e-6 m/sec

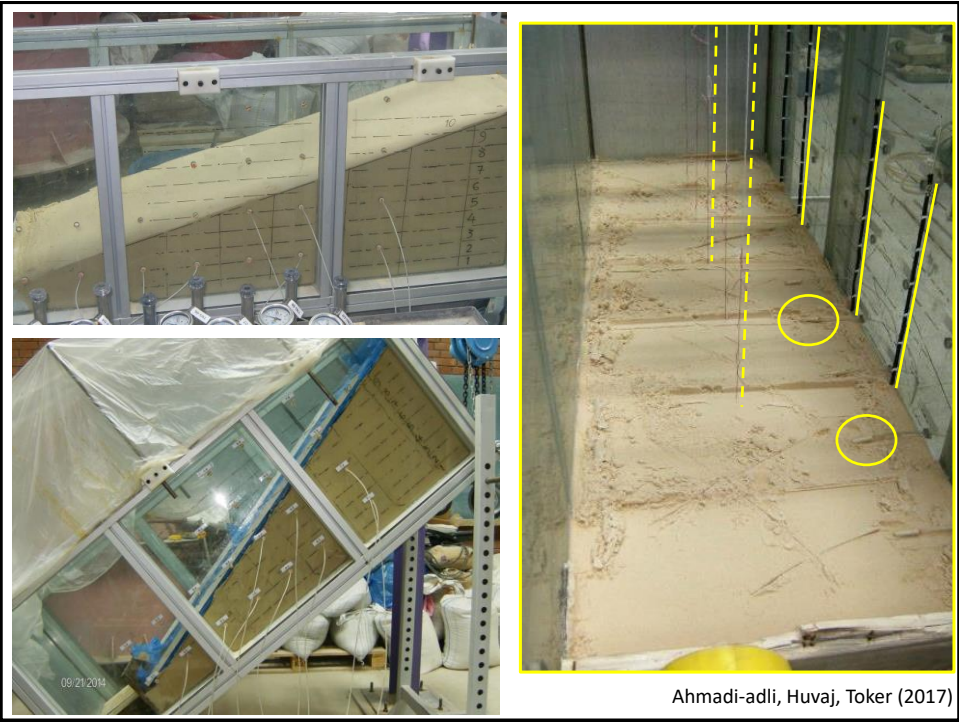
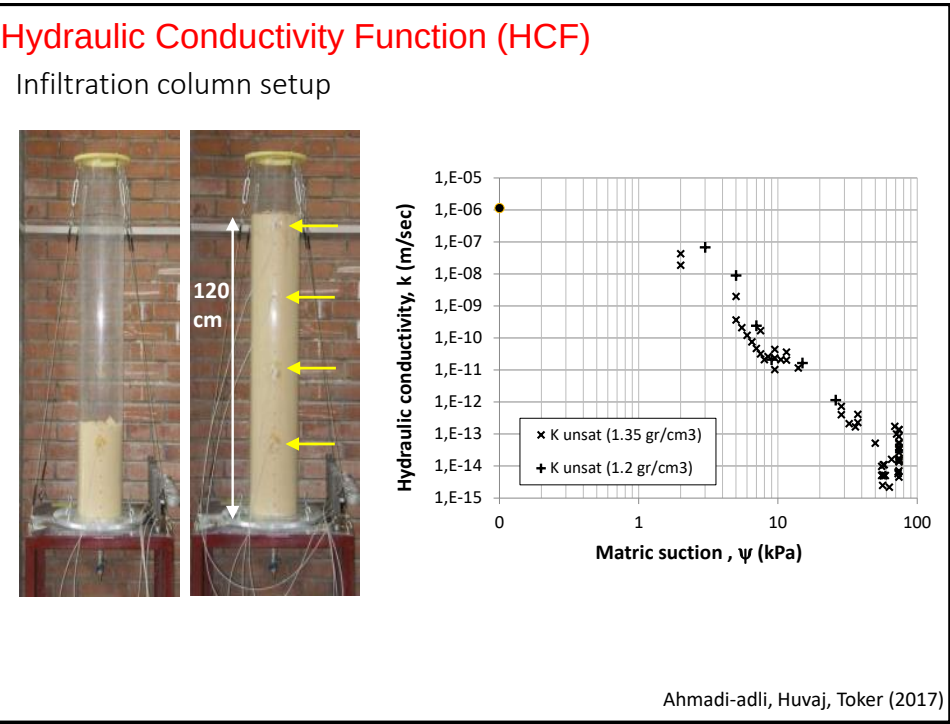
Ahmadi-adli, Huvaj, Tokar (2017)

Soil Water Characteristic Curve (SWCC)

- Hanging column setup (suction range 0-80 kPa)
- Pressure plate setup (suction range 50-1500 kPa)
- Capillary tube

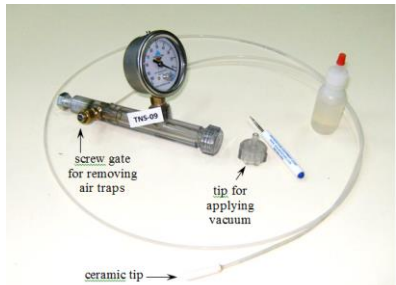


Ahmadi-adli, Huvaj, Tokar (2017)

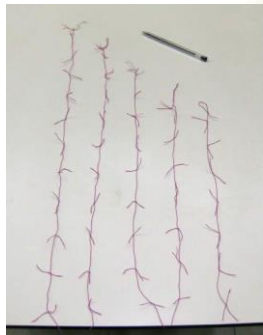
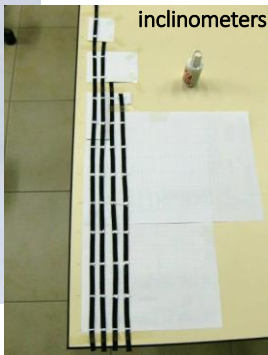


Flume model tests - instrumentation

- Miniature tensiometers,
- PDCR miniature pore pressure transducers
- Inclinometers

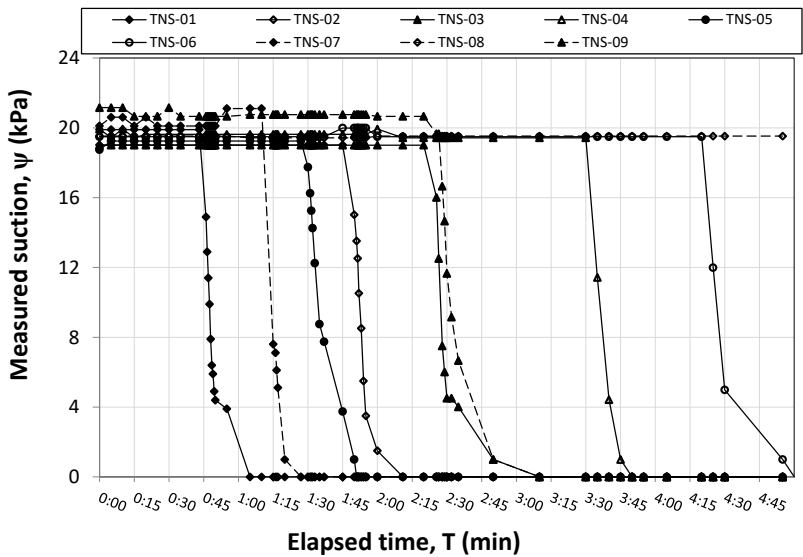


PDCR

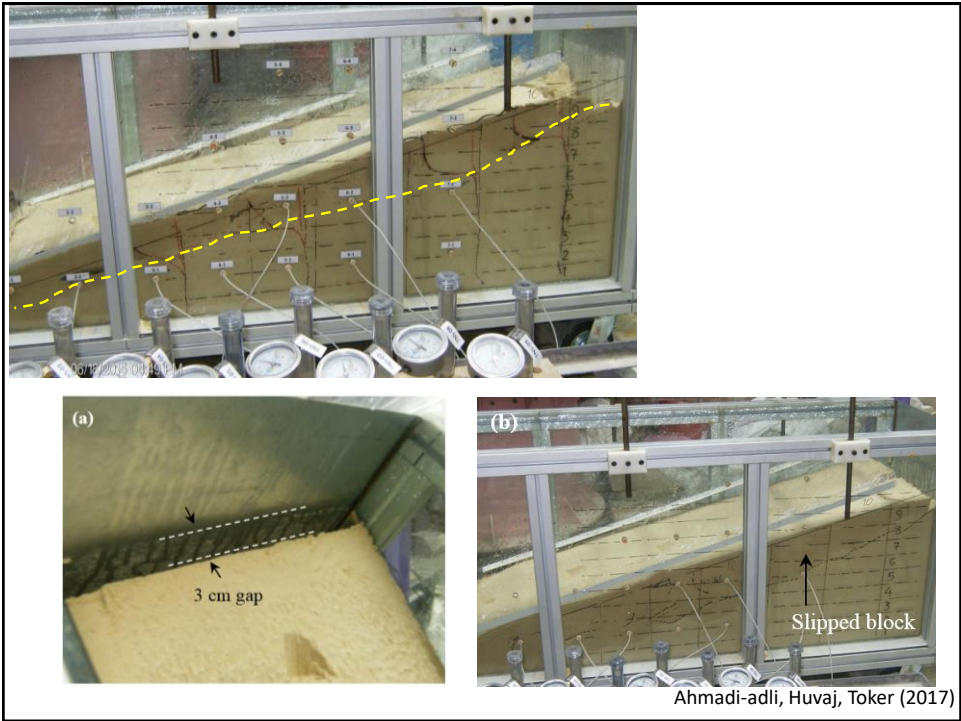
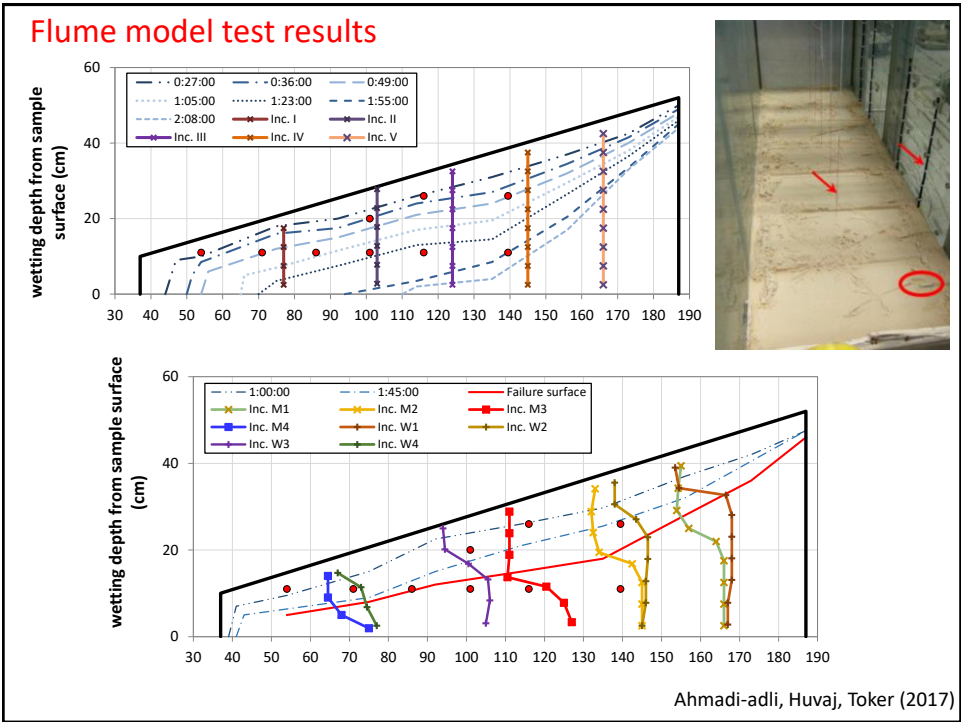


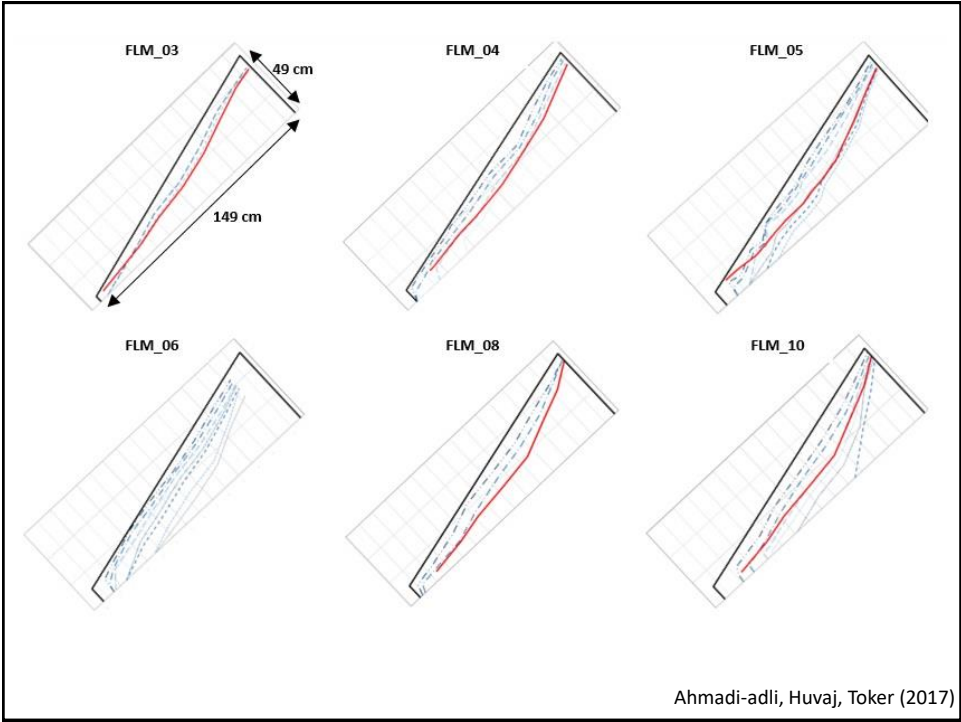
Ahmadi-adli, Huvaj, Toker (2017)

Flume model test results

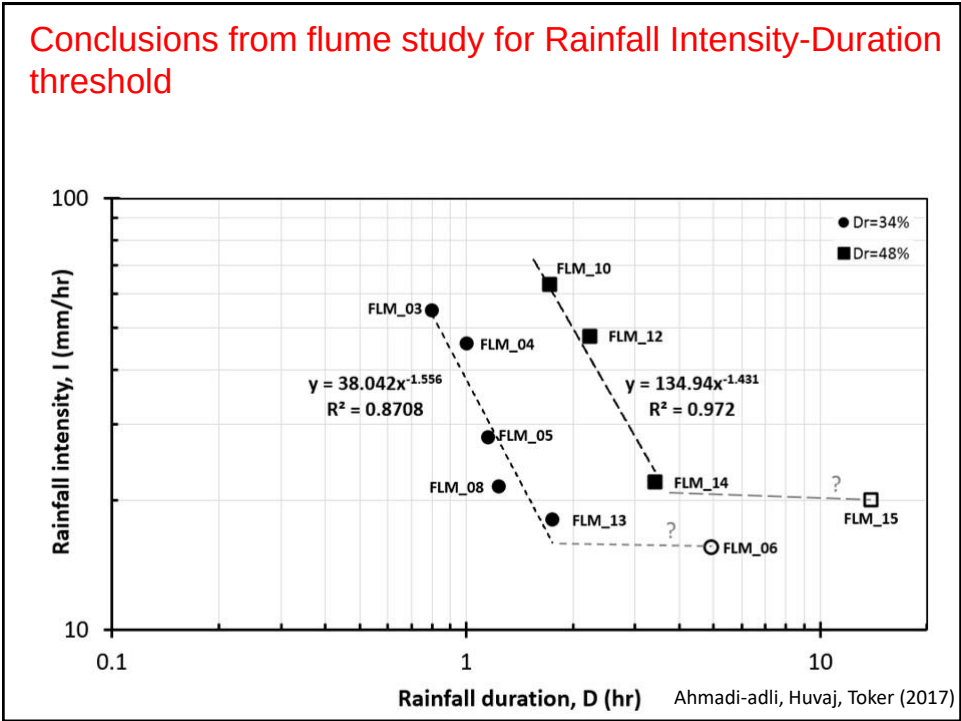


Ahmadi-adli, Huvaj, Toker (2017)

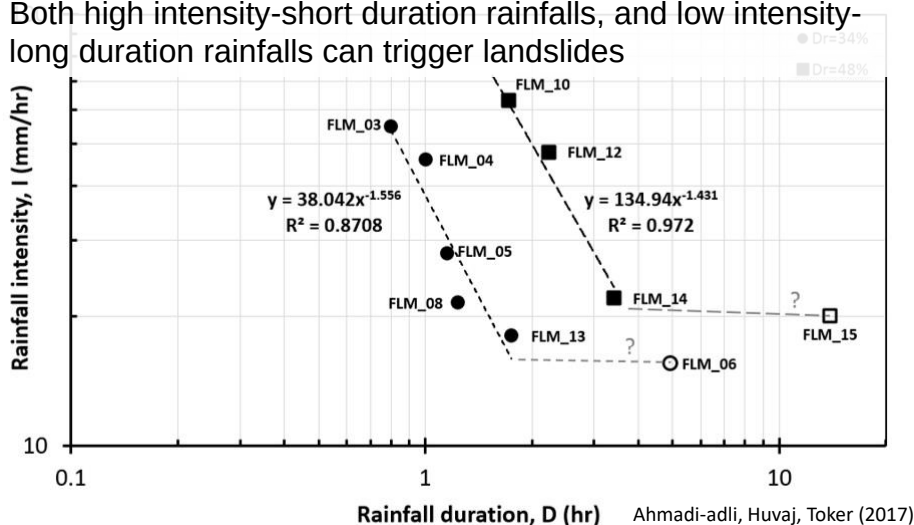




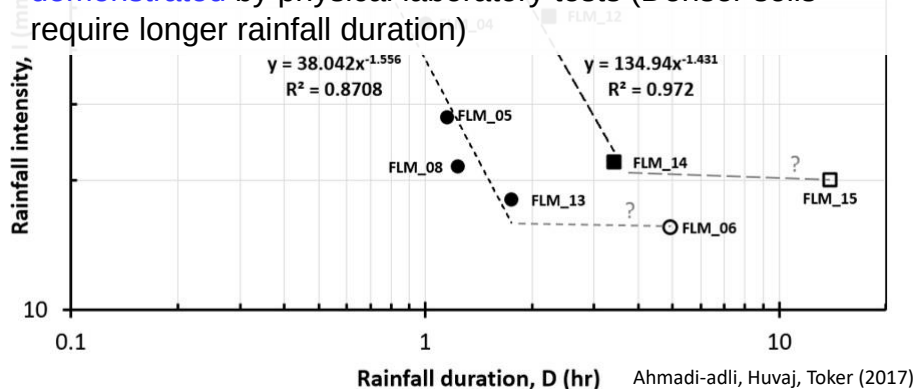
Conclusions from flume study for Rainfall Intensity-Duration threshold



- Laboratory flume tests on a clean fine sand soil at two **relative densities (34 and 48%)** subjected to **different rainfall intensities**
- the rainfall **intensity-duration thresholds** that would trigger a landslide (I-D plots) is obtained physically in the laboratory.
- Both high intensity-short duration rainfalls, and low intensity-long duration rainfalls can trigger landslides

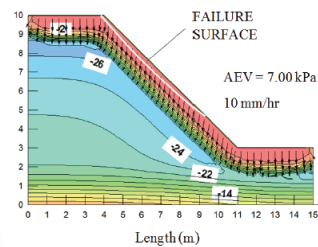
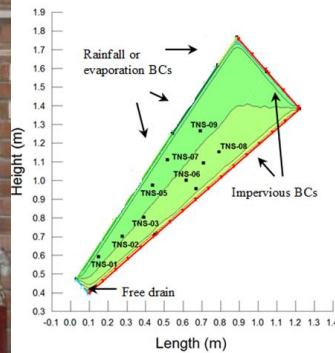
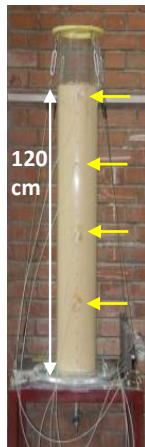


- The shape of the I-D threshold is demonstrated to be **mostly linear relation in log-log plot** for the soil used in this study.
- However, **below a certain rainfall intensity (15 mm/hr in this study) landslides are not triggered** in unsaturated soil (i.e. the I-D plot seems to be asymptotic to the rainfall intensity that is equal to gravity drainage).
- The **effect of the density of the soil on the I-D threshold is demonstrated** by physical laboratory tests (Denser soils require longer rainfall duration)



Numerical simulations

- Numerical modeling of infiltration column and flume tests
- Numerical modeling / parametric study
 - finite slope (2D)
 - Infinite slope (1D)



Validation of Flow Model

Infiltration column test of (Ahmadi-adli, 2014)

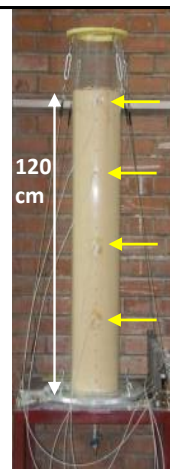
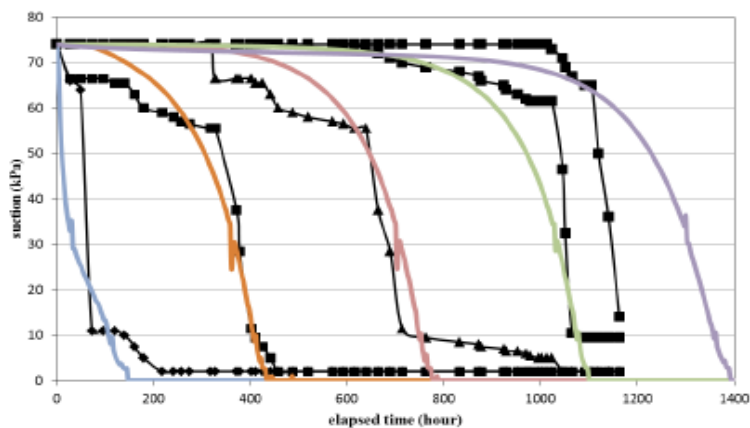
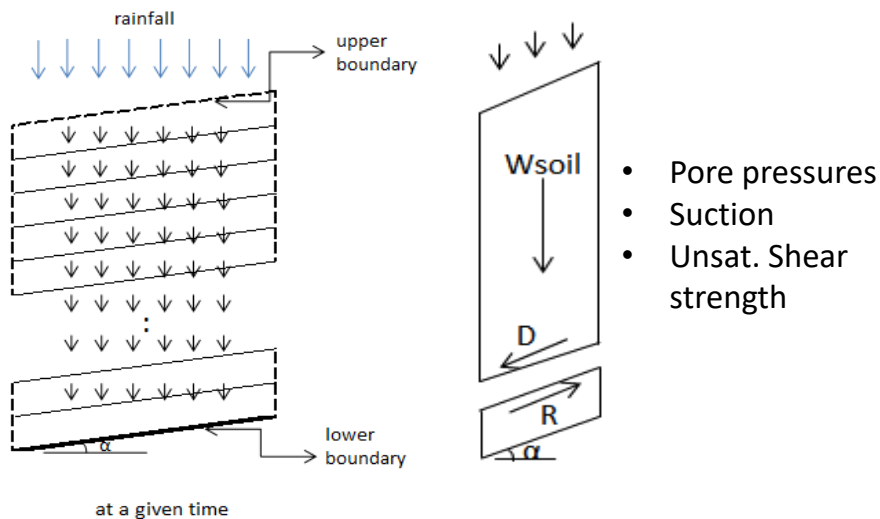


Figure 3. 15. The comparison of experimental results and the results of simulations. Curves with data points illustrate the experimental results and smooth curves illustrate simulation results.

Kenanoglu (2017) METU M.S. Thesis

Numerical simulations → infinite slope (MATLAB code)

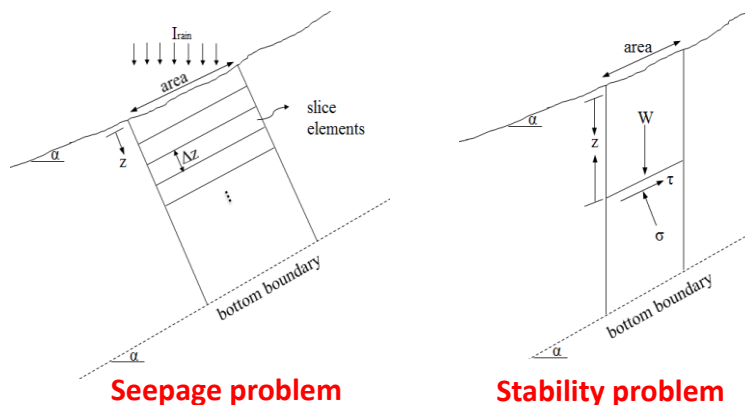


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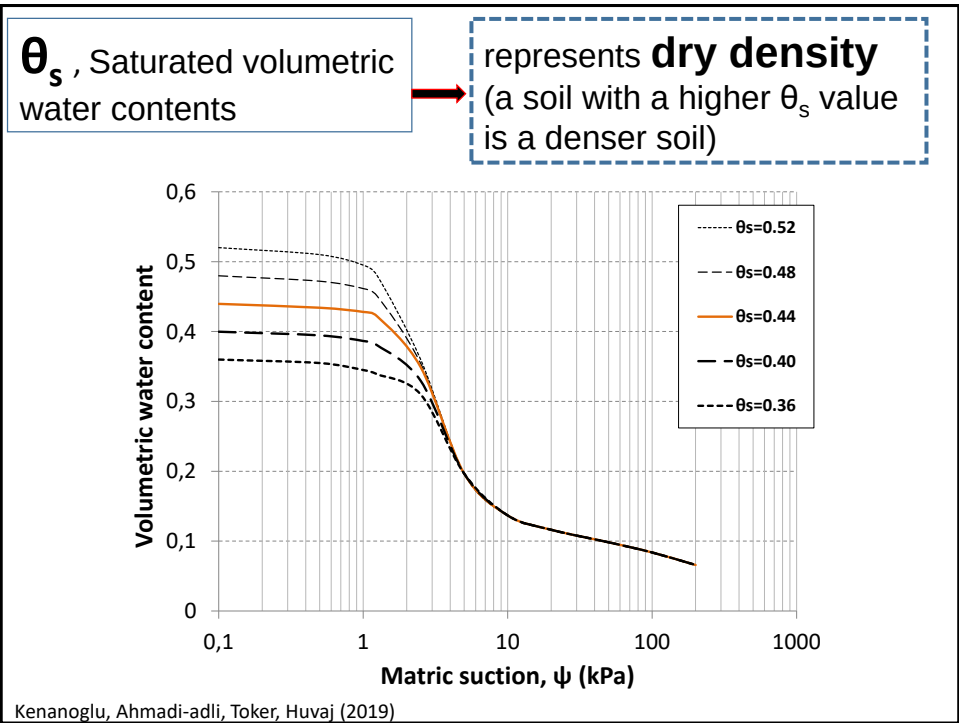
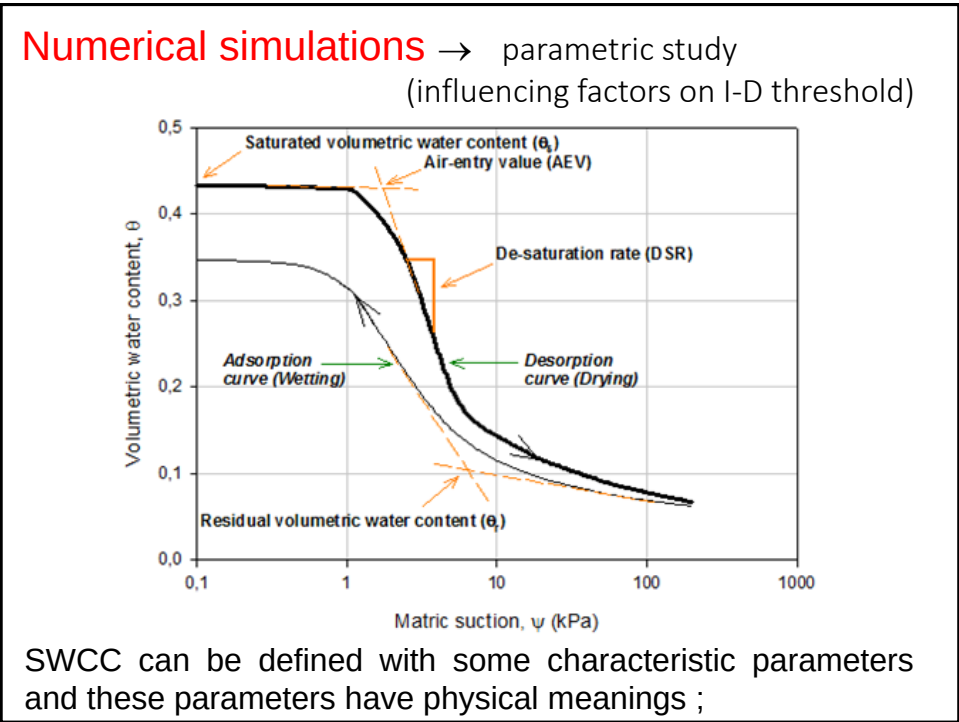
Hydromechanical numerical modelling

Rainfall-induced landslides:

- Wetting front propagation perpendicular to the slope surface
- Sliding surface parallel to ground surface (infinite slope)

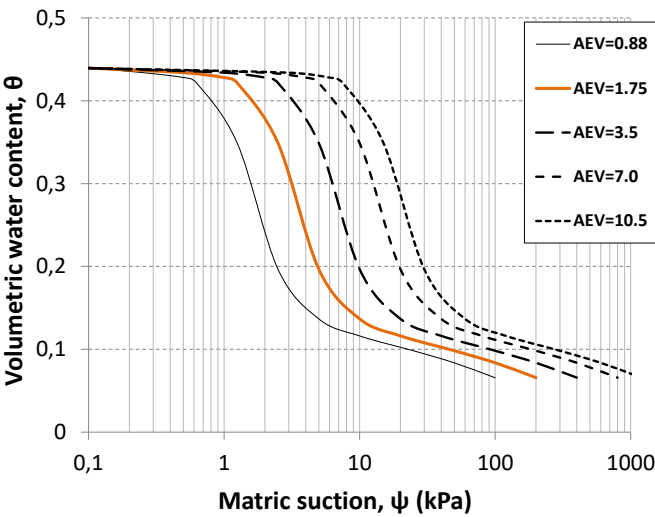


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AEV, Air entry value

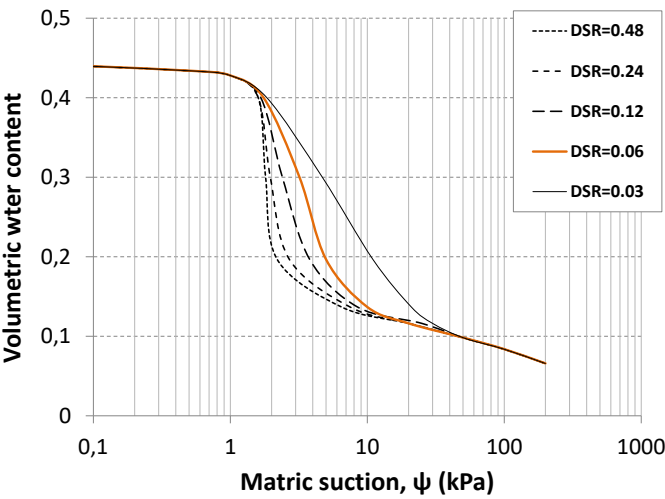
represents **gradation** (a soil with a higher AEV is a finer grained soil)



Kenanoglu, Ahmadi-adli, Toker, Huvaj (2019)

DSR, De-saturation rate

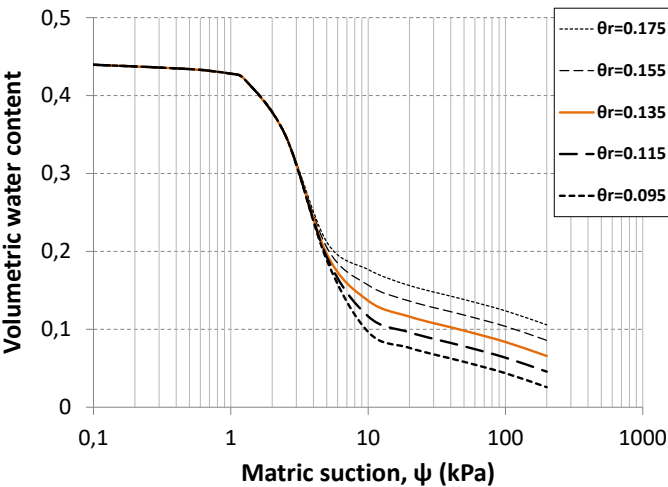
represents **uniformity** (the higher DSR the more uniform grain size dist.)



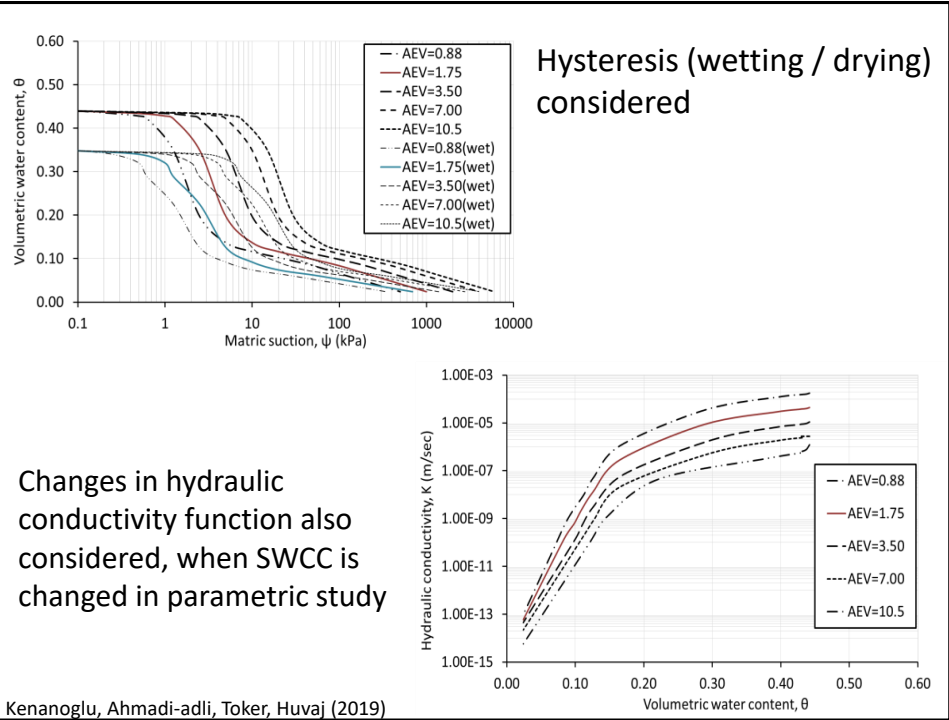
Kenanoglu, Ahmadi-adli, Toker, Huvaj (2019)

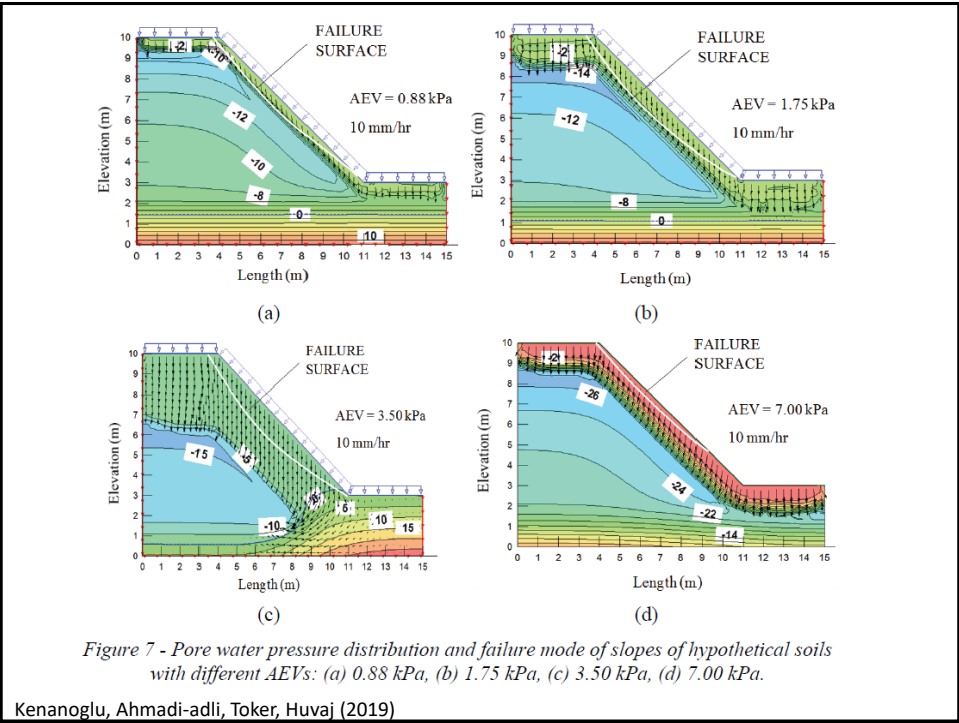
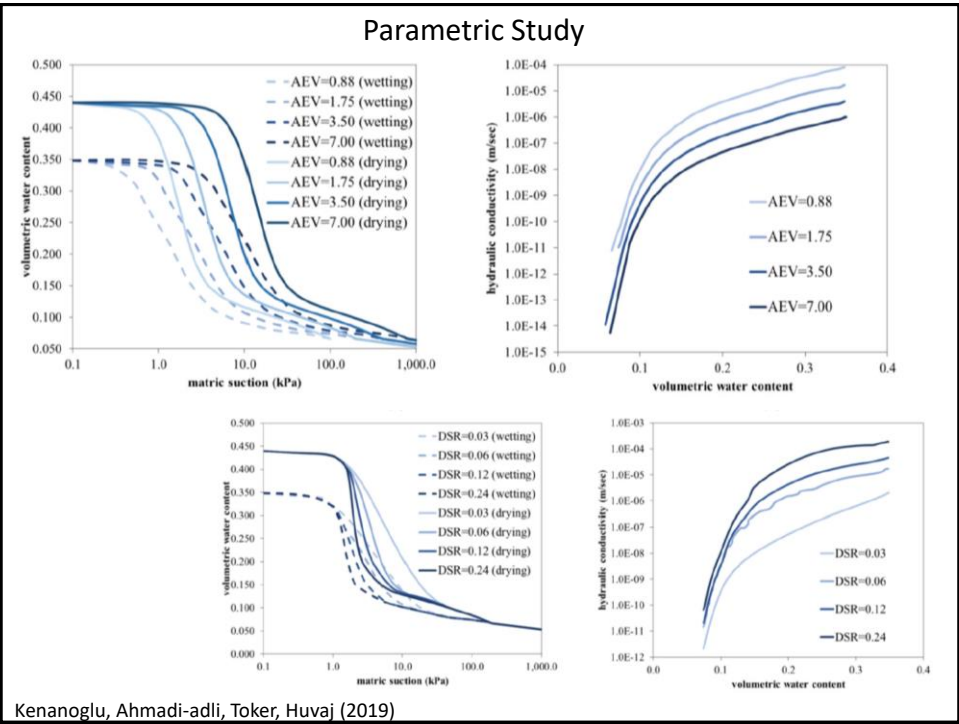
θ_r , Residual volumetric water contents

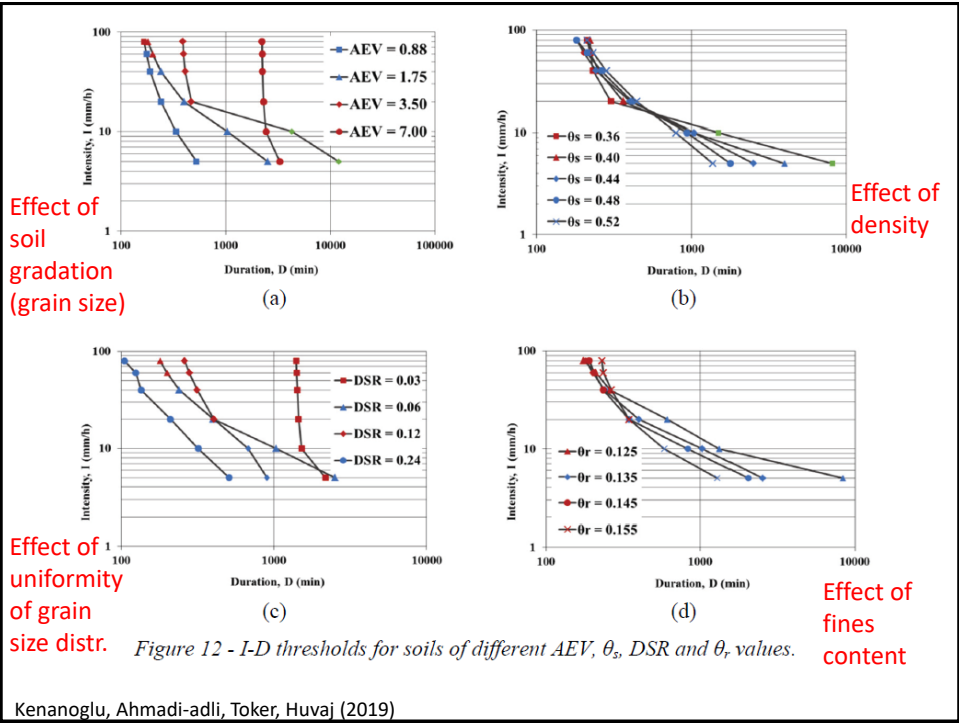
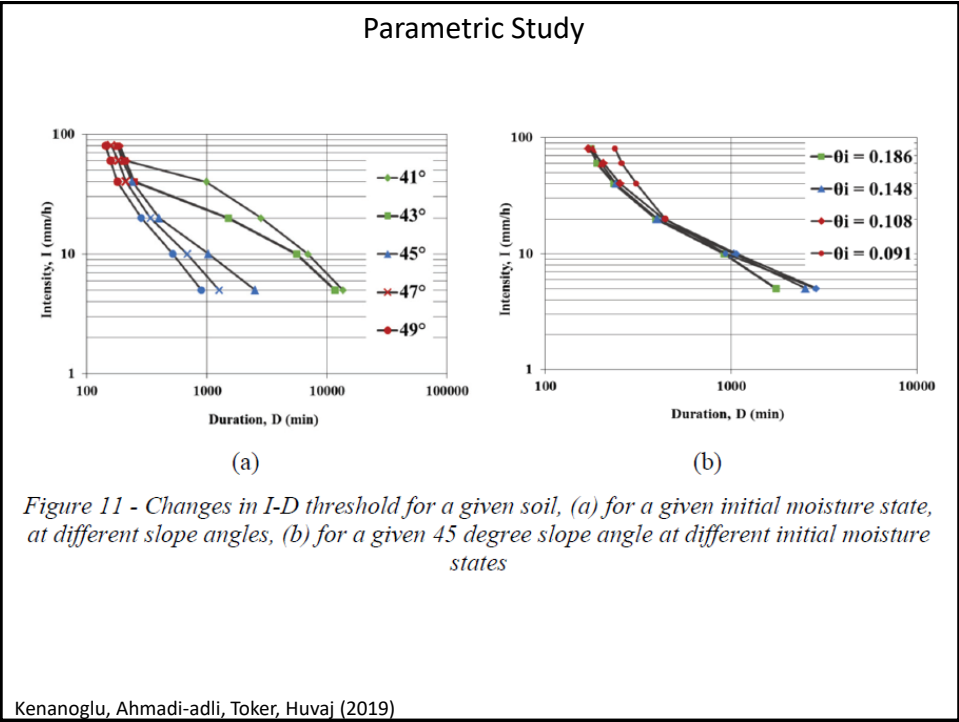
represents **fines content**
(as the fines content of soil increases, θ_r increases)



Kenanoglu, Ahmadi-adli, Toker, Huvaj (2019)







Conclusions from numerical (parametric) study

- different unsaturated soil properties lead to different intensity-duration thresholds for the same slope geometry.
- Unsaturated soil properties such a **SWCC and HCF** play a **critical role** in the behavior of unsaturated slopes and in rainfall-triggering of landslides.
- The intensity-duration threshold that triggers a landslide can be computed given that the unsaturated hydraulic and shear strength properties of the soil are known.
- Both “high intensity short duration” rainfalls and “low intensity long duration” rainfalls can cause landslides in unsaturated soils, as characterized by I-D thresholds.
- Among the parameters considered, **air entry value** (which is related to grain size) seems to be the most influential parameter on the rainfall I-D threshold.

Kenanoglu, Ahmadi-adli, Toker, Huvaj (2019)

- Based on the analyses carried out in this study for rainfall intensities between 5 - 80 mm/hr it is observed that **I-D threshold that triggers a landslide is nonlinear in a log-log plot.**
- A high-intensity rainfall may trigger a landslide in a **coarser soil** in shorter duration in comparison to a **finer soil**. For finer grained soils, time to failure is independent of rainfall intensity above a certain level. This is because above that certain intensity, only surface runoff increases and infiltration into the soil does not change.
- Three distinct **failure mechanisms** (or causes of failure) are identified: (A) surface erosion (mostly occurs at high intensity rainfall events), (B) failure due to suction decrease (generally at lower cumulative amounts of rainfall), (C) positive pore water pressure development.

Kenanoglu, Ahmadi-adli, Toker, Huvaj (2019)

Rainfall triggered landslides in Turkey



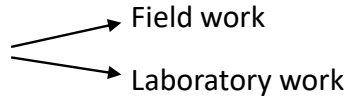




Typical characteristics of rainfall-triggered landslides in Turkey

- They are generally 1-5 m deep
- They occur on steep slopes (> 40 degrees)
- Classified as “fast landslides” (>1.8 m/hr,
Cruden and Varnes, 1996)
- Ground water table is well below the ground surface, soils are unsaturated initially
- Residual soils (weathering of rock in-place), of volcanic origin, pyroclastics, silty
- Translational (partly rotational) slides
- Soil properties?

Methodology



1. Field work

- Soil sampling at 12 landslide sites : about 40 samples
- In-situ shear strength via hand vane



Üyetürk, Huvaj et al. (2019)

Some of the sampling sites



Soil sampling and hand vane process



Soil sampling with small tubes



Hand vane test

Üyetürk, Huvaj et al. (2019)

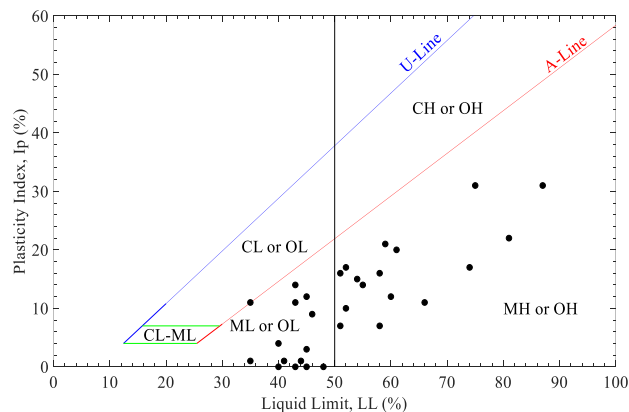
2. Laboratory work

- Soil classification
- Organic content determination
- pH measurements
- Saturated hydraulic conductivity
- Soil-water retention curve (SWRC)
- Shear strength via:
 - Unconfined compression tests
 - **Direct shear tests (on intact and reconstituted samples)**

Üyetürk, Huvaj et al. (2019)

Results

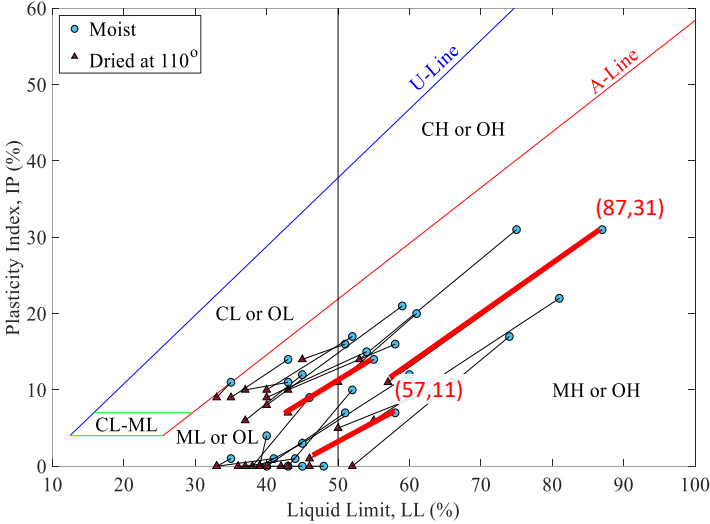
- Soils are mostly fine-grained, silty soils.
- They are **classified** as ML, MH, **OH (?)**, SM
- **Organic content (%)** are in the range of **1.8 % to 12.1 %**
- **pH values** are in the range of **3.3 to 5.6 (Acidic)**



Huvaj and Üyetürk (2018)

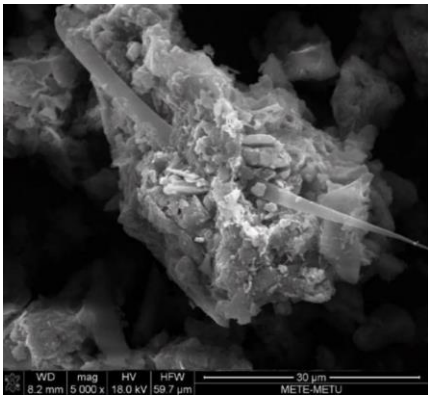
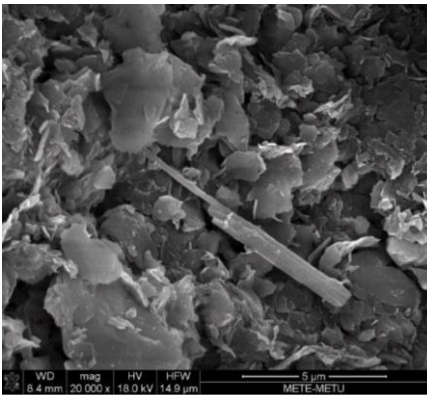
Results

Drying decreases Atterberg limits.
It may even change the soil classification



Huvaj and Üyetürk (2018)

Based on XRD and SEM study
they contain halloysite mineral



Huvaj and Üyetürk (2018)

Unconfined compression tests

- Cu range is **10 to 52 kPa**
- High void ratios (**0.81-1.58**)

Hand Vane Test (in-situ)

- Peak Cu = **42 to 103 kPa**
- Remolded Cu = **4 to 17 kPa**
- **Sensitivity = 2.5 to 16.2**
 - **Medium to extra sensitive** (Skempton and Northey 1952)

Üyetürk, Huvaj et al. (2019)

Methodology – Direct shear tests

140 direct shear tests were performed (**shearing time 3-8 hours**)

1. Intact specimens

- Saturated tests
- Unsaturated tests
(with field water content)

Normal stress range: 14 to 65 kPa



2. Reconstituted specimens

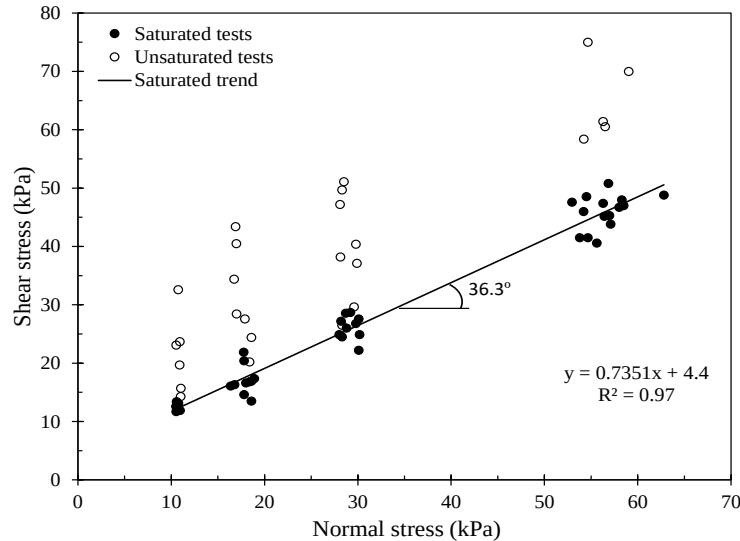
- Field dry-density
- Sr=60%
- Sr=80%
- Saturated



The main reasons for reconst. tests are to obtain uniform specimens and to study different Sr
Üyetürk, Huvaj et al. (2019)

Results

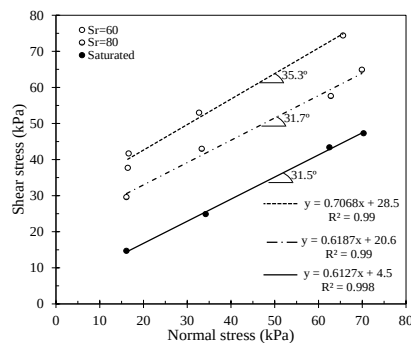
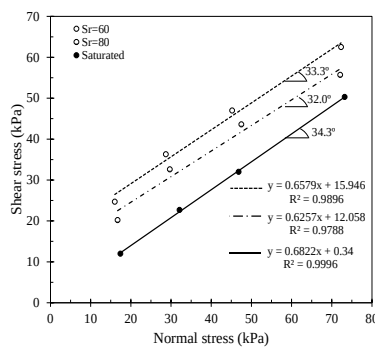
Saturated failure envelope for **intact** specimens



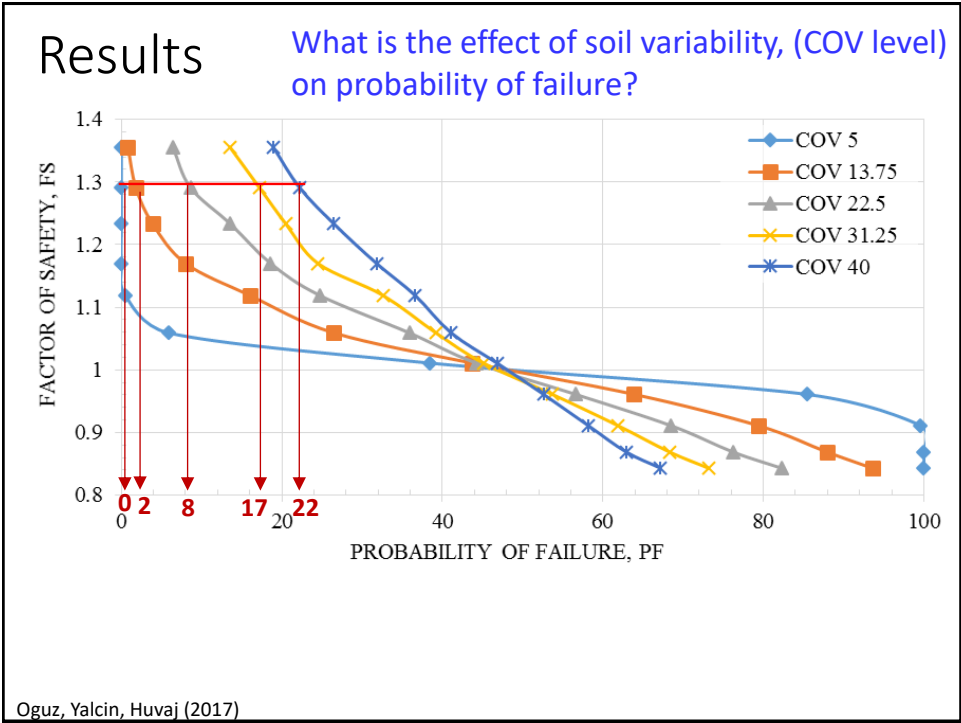
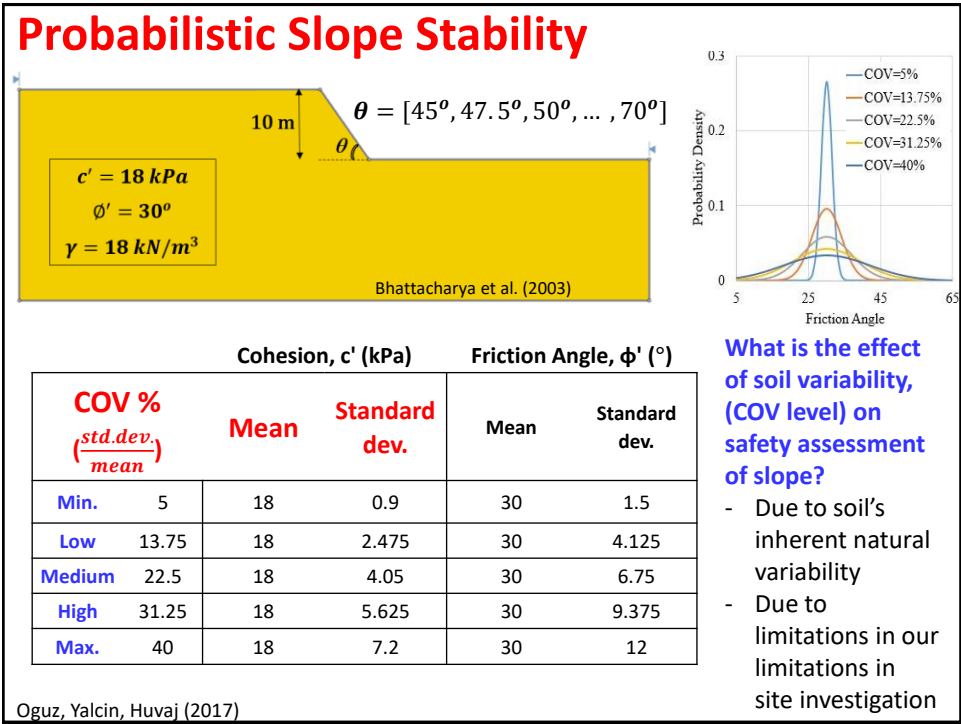
Üyetürk, Huvaj et al. (2019)

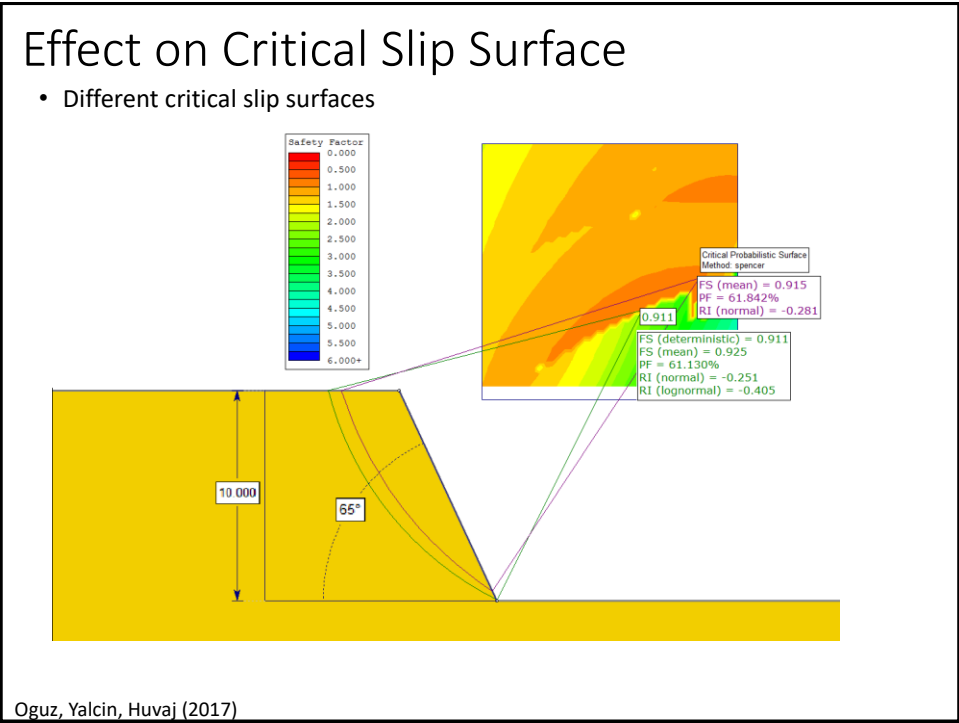
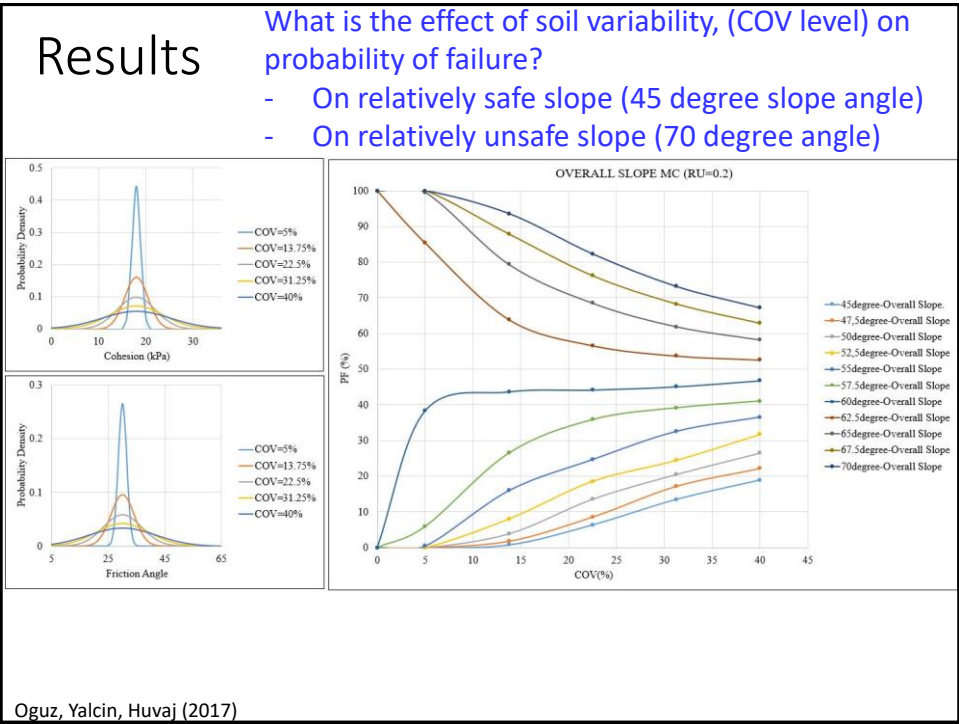
Results – Reconst. direct shear tests

- **Failure envelope** is found to be **linear** (mostly)
- Friction angles for different S_r cases are generally found to be similar
- Φ range: 30.4° to 34.4° (saturated)
- **Similar friction** angles with **intact specimens**



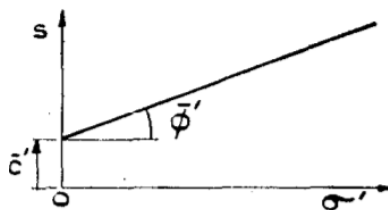
Üyetürk (2019) METU M.S. Thesis





Effect of Cross Correlation of parameters

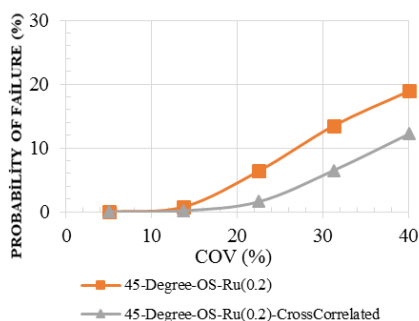
- In reality, soil parameters are **not independent random variables**.
- Strength parameters were negatively cross correlated:
coefficient of correlation $\rho = -0.5$



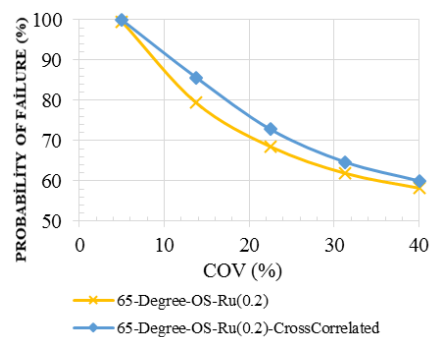
Oguz, Yalcin, Huvaj (2017)

Effect of Cross Correlation

Decrease in PF if FS > 1



Increase in PF if FS < 1



Oguz, Yalcin, Huvaj (2017)

Conclusions from probabilistic slope stability study

- Deterministic limit equilibrium analysis is not always sufficient for determination of the location of the most critical failure surface.
- PF and the critical failure surface is significantly influenced by COV level, the consideration of cross correlation.
- The inverse relation between FS and PF has been demonstrated to be nonlinear and the COV level has significant effect on this relationship.
- Slopes traditionally considered as safe (deterministic $FS > 1.00$) may have high PF values depending on the COV level.

Oguz, Yalcin, Huvaj (2017)

Conclusions from probabilistic slope stability study

- Increase of COV level causes increase in PF value for slopes with deterministic $FS > 1.00$.
- For slopes having deterministic $FS < 1.00$, the effect is reverse.
- Considering cross correlation between cohesion and friction angle significantly decreases PF for slopes having deterministic $FS > 1.00$, but increases for others.

Oguz, Yalcin, Huvaj (2017)

Random Finite Element Method

RFEM



[Probabilistic Methods in Geotechnical Engineering](#) pp 317-346 | [Cite as](#)

The Random Finite Element Method (RFEM) in Slope Stability Analysis

Authors

Authors and affiliations

D.V. Griffiths, Gordon A. Fenton

Chapter

3

6

2.2k

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Abstract

The paper investigates the probability of failure of a cohesive slope using both simple and more advanced probabilistic analysis tools. The influence of local averaging on the probability of failure of a test problem is thoroughly investigated. In the simple approach, classical slope stability analysis techniques are used, and the shear strength is treated as a single random variable. The advanced method, called the random finite element method (RFEM), uses elastoplasticity combined with random field theory. The RFEM method is shown to offer many advantages over traditional probabilistic slope stability techniques, because it enables slope failure to develop naturally by “seeking out” the most critical mechanism. Of particular importance in this work, is the conclusion that simplified probabilistic analysis, in which spatial

Random Finite Element Method

RFEM



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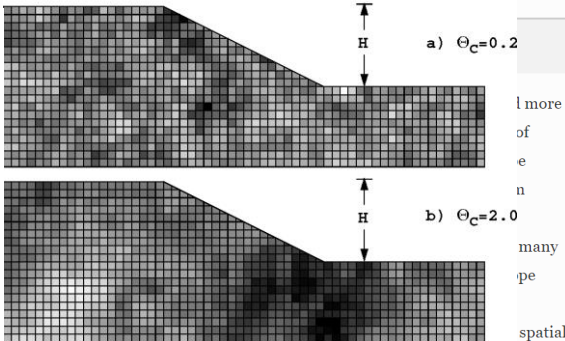
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RFEM combines random field theory, for modelling spatial variability, with the finite-element method (FEM), for modelling geotechnical response, within a Monte Carlo simulation process (Fenton & Griffiths, 2008).

Small spatial correlation length

Large spatial correlation length



a) $\Theta_c = 0.2$

b) $\Theta_c = 2.0$

l more of e n

many pe

spatial

39

EFFECTS OF SPATIAL VARIABILITY OF MARGINAL FILLS ON
EXTERNAL STABILITY OF REINFORCED SLOPES

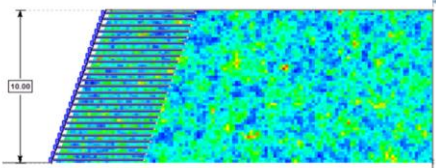
Muhammet DURMAZ¹ Nejan HUVAJ^{2*} Atalay Mert TURGUT³ Nur ÖZTÜRK³

Why consider soil variability in MSEW?
Aren't they made of clean gravel, and well compacted by us?

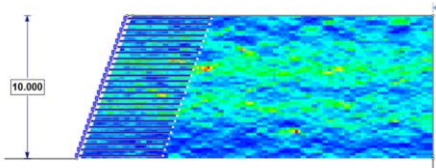


- using on-site available fill material containing some fines content, instead of obtaining and transporting clean granular materials ?
- economic and environmental benefits, in terms of saving natural resources (such as sand and gravel), reduced construction waste and waste disposal cost, sustainability and reduced carbon footprint of projects. Waste materials from different industries, such as mixtures of fine-grained and coarse-grained waste materials can be considered as a fill.
- However, when using on-site fill material, which is a mixture of coarse grained and up to 40% fine grained soils, the properties of the fill are more variable.
- Spatial correlation length.... is considered

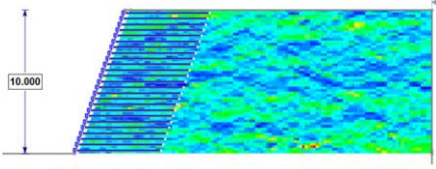
Durmaz, Huvaj et al. (2019)



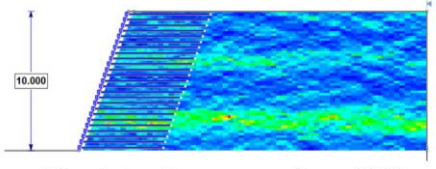
(a) isotropic spatial variable case.



(b) anisotropic spatial variable case



(c) anisotropic case, sample no. 200



(d) anisotropic case, sample no. 2993

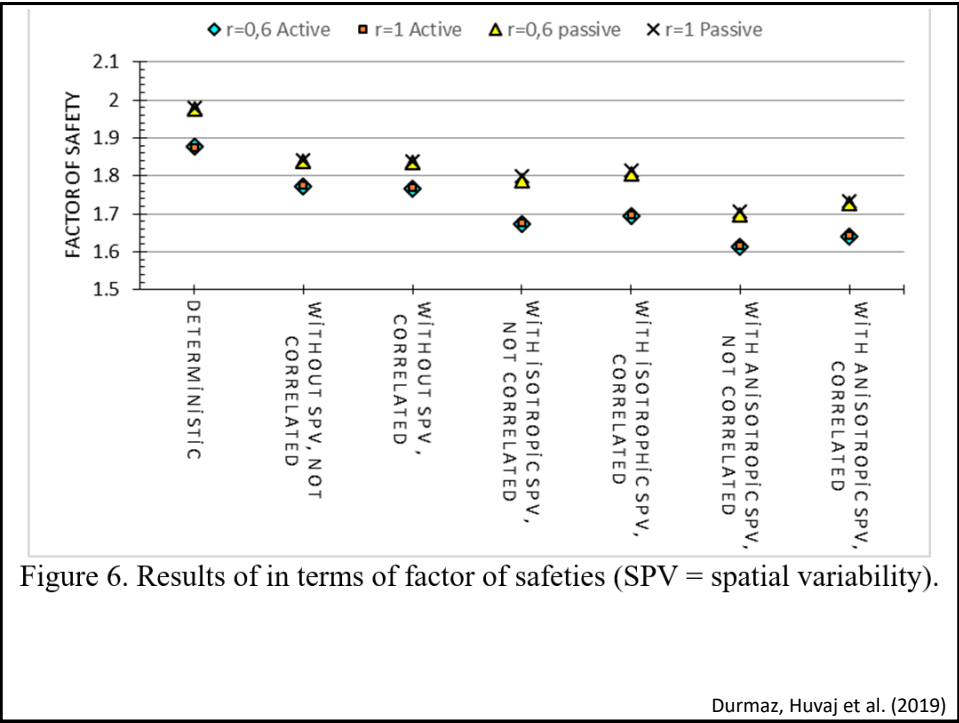
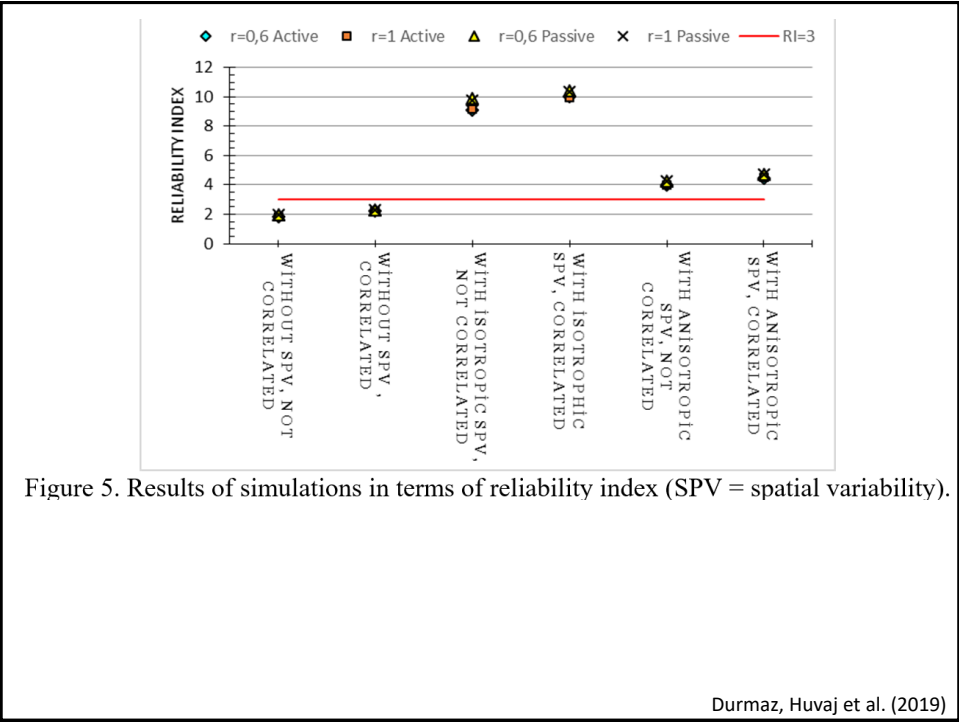
Figure 1. Examples of distribution of material properties: cohesion, c' .

- different generations of random fields, i.e. spatial distribution from a log-normal statistical distribution, of cohesion, c' , having mean value of 10 kPa and COV=0,40 (i.e. 40%), for a 10-m high reinforced soil slope in this study.

Table 1. Probabilistic marginal fill properties.

	Mean	Standard dev.	Relative min	Relative max
Cohesion, c' (kPa)	10	4	10	20
Unit Weight, γ (kN/m ³)	17.5	1.75	2.5	5.5
Friction Angle, ϕ' (°)	33	13.2	18	17

Durmaz, Huvaj et al. (2019)



Random Material Point Method, RMPM

Wang, B. et al. (2016) *Géotechnique Letters* 6, 113–118, <http://dx.doi.org/10.1680/jgele.16.00019>

Slope failure analysis using the random material point method

B. WANG*, M. A. HICKS* and P. J. VARDON*

The random material point method (RMPM), which combines random field theory and the material point method (MPM), is proposed. It differs from the random finite-element method (RFEM), by assigning random field (cell) values to material points that are free to move relative to the computational grid rather than to Gauss points in a conventional finite-element mesh. The importance of considering the effects of both large deformations and the spatial variability of soil strength properties in slope stability analyses is highlighted, by comparing RMPM solutions with RFEM and deterministic MPM solutions for an idealised strain-softening clay slope characterised by a spatially varying undrained shear strength. The risks posed by potential slides are quantified by the extent of retrogressive failure –

Random Material Point Method, RMPM

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Random fields are numerically generated predictions of the spatial variability of a property over the problem domain.

These are based on (a) an assumed probability density function, characterized by the mean property value μ and standard deviation σ ,

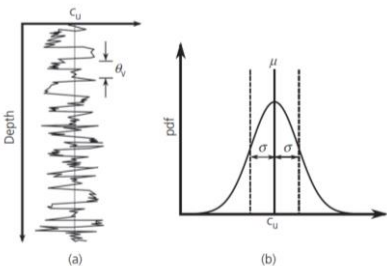
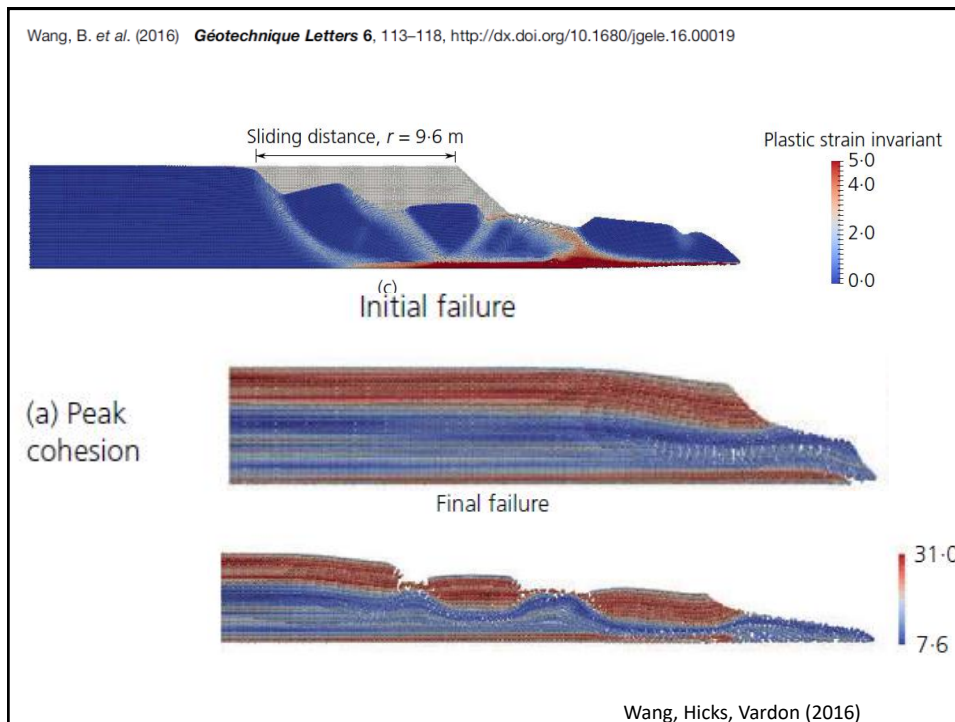


Fig. 2. Statistical measures of c_u variability (after Hicks & Samy, 2002): (a) variation of c_u with depth, (b) probability density function of c_u



Deterministic and probabilistic analyses

Risk and probability tools have reached a degree of maturity and breadth that make them effective to use in practice. They provide more insight than deterministic analyses alone. They help reduce uncertainty and focus on safety and cost-effectiveness.

Integrating deterministic and probabilistic analyses in a complementary manner brings together the best of our profession, including the required engineering judgment from the geotechnicians and from the risk analysis proponents.



Lacasse, 2015

Deterministic analyses
give an impression of certainty;

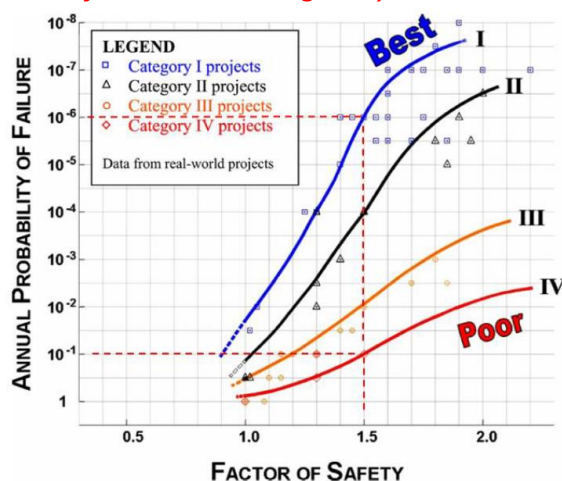
Probabilistic analyses
complete the picture by making explicit
the uncertainties and their effects;



For improved geotechnical practice,
we need both.

Lacasse, 2015

for a slope with deterministic FS value of 1.50, PF can be decreased from 10^{-1} to 10^{-6} , or to any desired level, **by increasing level of engineering (extensive site investigation, laboratory testing, state-of-the-art analyses, monitoring etc.)**



Silva F., Lambe T. and
Marr W. (2008).
"Probability and risk of
slope failure."

Relation between level of engineering and probability of failure

I would like to thank to my students and
collaborators...

nejan@metu.edu.tr