PROPOSAL PENGABDIAN KEPADA MASYARAKAT

2D & 3D PLAXIS ADVANCED COURSE

TIM PENYUSUN:

INDRA NOER HAMDHAN, DR. TECHN., S.T., M.T.

PROGRAM STUDI TEKNIK SIPIL
FAKULTAS TEKNIK SIPIL DAN PERENCANAAN
INSTITUT TEKNOLOGI NASIONAL
BANDUNG
2018

HALAMAN PENGESAHAN

1. Judul : 2D & 3D Plaxis Advanced Course
2. Pelaksana : Dr. tech. Indra Noer Hamdan, ST., MT.

   NIP : 120030105
   Pangkat/Golongan : Lektor/III D
   Jurusan : Teknik Sipil
   Bidang Keahlian : Geoteknik

3. Bentuk Kegiatan : Workshop
4. Waktu Kegiatan : 3 – 7 Desember 2018
5. Sumber Dana : ASEA-UNINET dan RKAT Jurusan Teknik Sipil
6. Jumlah Dana : Rp. 65.000.000

Bandung, 12 November 2018

Pelaksana	Ketua Jurusan Teknik Sipil
(Dr. tech. Indra Noer Hamdan, ST., MT.)	(Dr. tech. Indra Noer Hamdan, ST., MT.)

Mengetahui

Kepala LP2M Itenas

itenas LPPM

(Dr. Tarsisius Kristyadi, ST., MT.)

PROPOSAL KEGIATAN
2D & 3D Plaxis Advanced Course

Latar Belakang

Dalam dunia teknik sipil sendiri, ilmu geoteknik merupakan langkah awal terbentuknya suatu infrastruktur. Tanpa ilmu geoteknik mustahil suatu infrastruktur dapat berdiri dengan kokoh, karena ilmu geoteknik merupakan cabang dari ilmu teknik sipil yang mempelajari ilmu tanah dimana di dalam ilmu ini akan dikupas tentang kemampuan tanah menahan beban, sehingga pembangunan infrastruktur dapat direncanakan sebaik mungkin agar dapat berdiri kuat dan kokoh sesuai dengan umur yang telah direncanakan sebelumnya. Perencanaan infrastruktur dalam bidang geoteknik dapat dilakukan melalui modeling sebuah perangkat lunak bernama PLAXIS. Maka, diperlukan dasar pengetahuan dan pelatihan yang baik untuk dapat menggunakan program yang dirancang khusus untuk menyelesaikan permasalahan geoteknik secara maksimal dan tepat guna. Pelatihan ini dirancang untuk memberikan tuntunan penyelesaian berbagai persoalan geoteknik melalui **2D & 3D Plaxis Advanced Course**.

Tujuan

Tujuan dari kegiatan **2D & 3D Plaxis Advanced Course** ini adalah untuk memberikan wawasan, pengetahuan, praktik, serta wadah diskusi kepada para peserta baik yang berasal dari akademisi maupun praktisi yang bergerak di bidang geoteknik serta membutuhkan *upgrading* keahlian dan pengetahuan terkait *permasalahan geoteknik* melalui perangkat lunak PLAXIS 2D dan PLAXIS 3D.

Rencana Mekanisme Pelaksanaan Kegiatan

Kegiatan ini dilaksanakan selama 5 hari**,** yakni pada 3 – 7 Desember 2018 selama 6 (enam jam setiap hari-nya, dari pukul 9.00 – 17.00 WIB.
Lokasi pelaksanaan kegiatan ini dilaksanakan di Bali.
Lingkup kegiatan pelatihan yang direncanakan terdiri dari pemberian materi-materi sebagai berikut:

- Introduction to finite element modeling
- Plasticity Mohr-Coulomb and hardening soil model
- Structural elements in Plaxis
- Initial stresses
- Footing on elasto-plastic soil
- Modeling of deep excavation
- Modeling groundwater
- Safety Factor in PLAXIS
- Excavation of building pit (HS)
- Excavation and Dewatering
- Modeling of undrained behaviour and consolidation
- Modeling of ground improvement

- Groundwater Flow Analysis in Dams
- Slope Stability for a Road Construction Project
- Modeling of embankment improved with PVD

Target Luaran

Target luaran untuk kegiatan **2D & 3D Plaxis Advanced Course** ini adalah meningkatan wawasan dan kemampuan tenaga pekerja dalam dunia geoteknik dalam hal pekerjaan perencanaan infrastruktur di Indonesia.

LAPORAN PENGABDIAN KEPADA MASYARAKAT

2D & 3D PLAXIS ADVANCED COURSE

PENYUSUN:

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1. Judul : 2D & 3D Plaxis Advanced Course
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5. Sumber Dana : ASEA-UNINET dan RKAT Jurusan Teknik Sipil
6. Jumlah Dana : Rp. 65.000.000

Bandung, 21 Januari 2019

Pelaksana	Ketua Jurusan Teknik Sipil
(Dr. techn. Indra Noer Hamdhan, ST., MT.)	(Dr. techn. Indra Noer Hamdhan, ST., MT.)

Mengetahui

Kepala LP2M Itenas

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LPPM

(Dr. Tarsisius Kristyadi, ST., MT.)

YAYASAN PENDIDIKAN DAYANG SUMBI
INSTITUT TEKNOLOGI NASIONAL
LEMBAGA PENELITIAN DAN PENGABDIAN KEPADA MASYARAKAT
Jl. PHH Mustapa 23, Bandung 40124 Indonesia, Telepon: +62-22-7272215 ext 157, Fax:022-720 2892
Web site: http://www.itenas.ac.id, e-mail: lpp@itenas.ac.id

SURAT KETERANGAN

MELAKUKAN KEGIATAN PENGABDIAN KEPADA MASYARAKAT
INSTITUT TEKNOLOGI NASIONAL
No. 025/C.02.01/LP2M/I/2019

Yang bertanda tangan di bawah ini,

Nama	: Dr. Tarsisius Kristyadi, S.T., M.T.
Jabatan	: Kepala
Unit Kerja	: LP2M-Itenas JL. P.K.H. Mustafa No.23 Bandung

Menerangkan bahwa,

Nama	NPP	Jabatan
Dr.techn. Indra Noer Hamdhan, S.T., M.T.	20030105	Committee & Lecture

Telah melakukan kegiatan Pengabdian kepada Masyarakat sebagai berikut :

Nama Kegiatan	:	2D Plaxis Advanced Course
Tempat	:	Bali
Waktu	:	03 - 07 Desember 2018
Sumber Dana	:	RKAT Jurusan Teknik Sipil Tahun 2018 dan Peserta Pelatihan

Demikian surat keterangan ini dibuat untuk dapat dipergunakan sebagaimana mestinya.

Bandung, 21 Januari 2019

Lembaga Penelitian dan Pengabdian kepada Masyarakat (LP2M) Itenas
Kepala,

itenas
LPPM

Dr. Tarsisius Kristyadi, S.T., M.T.
NPP 960604

YAYASAN PENDIDIKAN DAYANG SUMBI

INSTITUT TEKNOLOGI NASIONAL

Jl. PKH. Hasan Mustapa No.23 Bandung 40124 Indonesia, Telepon: +62-22-7272215, Fax: +62-22-7202892
Website: http://www.itenas.ac.id., e-mail: rektorat@itenas.ac.id

Form SPPP

SURAT PERINTAH PERJALANAN

PEGAWAI AKADEMIK

299/F.06/BSDM/ITENAS/XI/2018

1. Pejabat yang berwenang memberi perintah : Wakil Rektor Bidang Keuangan dan Umum

2. Pegawai yang ditugaskan

Nama	Unit Kerja	Jabatan
Dr. Techn. Indra Noer Hamdhani,S.T., M.	Jurusan Teknik Sipil	Lektor
~~Ikhya, S.T., M.T., M.M~~	~~Jurusan Teknik Sipil~~	~~Asisten Ahli~~
Suwarno	Jurusan Teknik Sipil	Tenaga Kependidikan

3. Tujuan Perjalanan : Pelatihan PLAXIS tahun 2018

4. Tempat : Nusa Dua Bali

5. Lama Perjalanan : 5 (Lima) hari

    a. Berangkat Tanggal : 3 Desember 2018

    b. Kembali Tanggal : 7 Desember 2018

Yang Menugaskan,	Verifikasi Kehadiran, Seminar, Lokakarya.
Wakil Rektor Bidang Keuangan dan Umum,	Panitia Penyelenggara,dll.
Tanggal, 30 November 2018	Tanggal, 4 - 12 - 2018
itenas INSTITUT TEKNOLOGI NASIONAL	Bali Tropic Resort & Spa Nusa Dua - Bali
(Yuniar, S.T., M.T.)	(I KETUT NATA / FOM.
	Nama jelas dan cap penyelenggara

***) SPPP ini harap dikembalikan ke BSDM setelah dibubuhi tanda tangan dan cap penyelenggara.**

itenas
Institut Teknologi Nasional

PLAXIS

TU Graz
Graz University of Technology

COMPUTATIONAL GEOTECHNICS COURSE

THIS CERTIFICATE IS PRESENTED TO

Dr. techn. Indra Noer Hamdhan

AS LECTURER IN THE

2D & 3D PLAXIS ADVANCED COURSE

Bali - Indonesia

3 - 7 December 2018

Prof. Helmut F. Schweiger
Computational Geotechnics Group
Institute for Soil Mechanics & Foundation Eng.
Graz University of Technology - Austria
(Course Leader)

Dr. Imam Aschuri, M.T.
Rector of Itenas Bandung

Andi Kartawiria, S.T., M.T.
Head of HATTI JABAR

Dr. William Cheang
Plaxis AsiaPac

itenas
Institut Teknologi Nasional

PLAXIS

TU Graz
Graz University of Technology

COMPUTATIONAL GEOTECHNICS COURSE

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Dr. techn. Indra Noer Hamdhan

AS COMMITTEE IN THE

2D & 3D PLAXIS ADVANCED COURSE

Bali - Indonesia

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Rector of Itenas Bandung

Andi Kartawiria, S.T., M.T.
Head of HATTI JABAR

Dr. William Cheang
Plaxis AsiaPac

COMPUTATIONAL GEOTECHNICS COURSE
(2D & 3D Plaxis Advanced Course)

Bali- Indonesia, 3 - 7 December 2018

Organized by:

Sponsored by:

Pre-training: Monday 3.12.2018

Session Pre-training:

3:00	4:00	CGT1	Introduction to PLAXIS 2D & 3D	Dr Cheang
4:00	5:00	CGT2	Training 1: Modelling with PLAXIS 2D and 3D	Dr Cheang/Indra/Franz

Day 1: Tuesday 4.12.2018

Session 1: Soil Behaviour and Models

8:30	9:15	CG1	Geotechnical Finite Element Modelling	Prof Schweiger
9:15	10:00	CG2	Plasticity and Mohr-Coulomb Soil Model	Prof Schweiger
10:00	10:15	Tea Break		
10:15	12:00	CG3	Exercise 1: Elastic and Elastoplastic Modelling of Strip Foundation	Dr Cheang
12:00	1:00	Lunch		

Session 2: Soil Models

1:00	2:00	CG4	Critical Soil Mechanics and Soft Soil Model	Prof Schweiger
2:00	3:15	CG5	Hardening Soil and HS-small Soil Models	Prof Schweiger
3:15	3:30	Tea Break		
3:30	4:15	CG6	Structural Elements in Plaxis	Dr Cheang
4:15	5:30	CG7	Exercise 2: Calibration of Soil Model using Soil Test	Dr Tschuchnigg

Day 2: Wednesday 5.12.2018

Session 3: Initial Stresses and Safety Analysis, Modelling of Excavations,

8:30	9:15	CG8	Modelling of Excavations	Prof Schweiger
9:15	10:00	CG9	Initial Stresses and Safety Factor Analysis	Prof Schweiger
10:00	10:15	Tea Break		
10:15	12:00	CG10	Exercise 3: Modeling of Excavation using MC, HS and HS-small	Dr Tschuchnigg
12:00	1:00	Lunch		

Session 4: Modelling of Groundwater, Drained, Undrained and Consolidation Condition

1:00	2:00	CG11	Modelling of Groundwater in PLAXIS	Dr Cheang
2:00	3:00	CG12	Modelling of Undrained Behaviour and Consolidation	Prof Schweiger
3:00	3:15	Tea Break		
3:15	4:00	CG13	Ground Improvement with Vertical Drains	Ikhya
4:00	5:30	CG14	Exercise 4: Modelling of embankment improved with vertical drains	Ikhya

Day 3: Thursday 6.12.2018

Session 5: Modelling of Embankments, Slopes and Unsaturated Soil Behaviour I

8:30	9:15	CG15	Utilization of Bamboo Pile-Mattress System as Soil Improvement for Embankment on Soft Soils	Prof Masyhur
9:15	10:00	CG16	Unsaturated Soils	Prof Schweiger
10:00	10:15	Tea Break		
10:15	12:00	CG17	Exercise 5: Slope Exercise	Dr Cheang
12:00	1:00	Lunch		

Session 6: Modelling of Embankments, Slopes and Unsaturated Soil Behaviour 2

1:00	2:00	CG18	Modelling of Full and Partially Saturated Slopes	Dr. Indra
2:00	3:15	CG19A	Exercise 6A: Slope Instability and Influence of Unsaturated Soil Behaviour	Dr. Indra
3:15	3:30	Tea Break		
3:30	4:30	CG19B	Exercise 6B: Evaluation of Slope Instability and Influence of Unsaturated Soil Behaviour	Dr. Indra

Day 4: Friday 7.12.2018

Session 7: Modelling of Ground Improvement

8:00	8:45	CG20	Modelling of Ground Improvement	Prof Schweiger
8:45	9:30	CG21	Concrete Model (SCM)	Prof Schweiger
9:30	9:45	Tea Break		
9:45	11:30	CG22	Exercise 7: Modelling of Improved Ground	Dr Tschuchnigg
11:30	1:30	Lunch + Friday Pray		

Session 8: POP Quiz

2:00	4:00

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CG18
Modelling of Slope Instability and Influence of Unsaturated Soil Behaviour

Indra Noer Hamdhan [1] **and Helmut F. Schweiger** [2]

[1] Civil Engineering Department
National Institute of Technology (Itenas) Bandung

[2] Computational Geotechnics Group
Institute for Soil Mechanics and Foundation Engineering
Graz University of Technology

CONTENTS

Definition of safety factor obtained by FEM
(available = characteristic value)

$$\eta_{fe} = \frac{\tan\varphi_{available}}{\tan\varphi_{failure}} = \frac{c_{available}}{c_{failure}}$$

Basically 2 possibilities to obtain factor of safety:

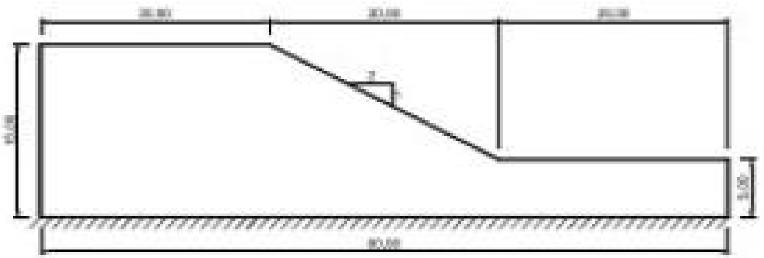
1: Calculation with characteristic parameters > automatic reduction of strength parameters of soil until equilibrium is no longer achieved in numerical analysis
Some FE-codes do this automatically > strength-reduction technique

2: Calculation with reduced parameters > perform *new* calculation with different factors until equilibrium is no longer achieved in numerical analysis
Some codes do this automatically

see also: e.g. Griffiths (1980), Naylor (1981), Brinkgreve & Bakker (1991), Matsui & San (1992)

Homogeneous, drained soil layer

Inclination of slope: 2:1



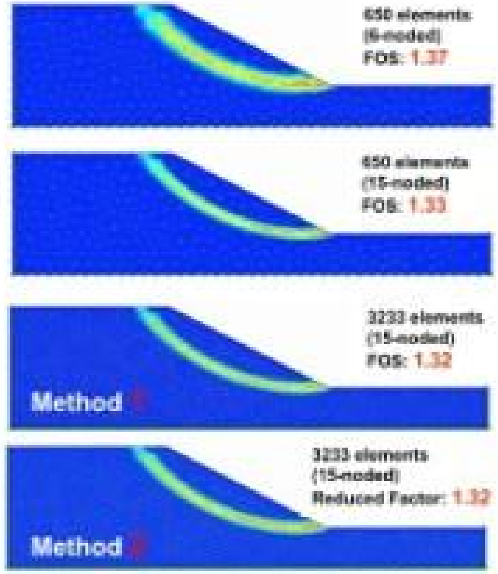
Soil parameters (Mohr-Coulomb failure criterion):
$\varphi' = 20.0$ [°] , $c' = 10.0$ [kN/m²]
$E = 10^5$ [kN/m²] , $\nu = 0.3$ [-] , $\gamma = 20.0$ [kN/m³]

Example from: Griffiths and Lane, Slope stability analysis by finite elements, Geotechnique 49, 387-403, 1999

Check of Mesh Dependency:

Coarse Mesh (650 elements):

Fine Mesh (3233 elements):

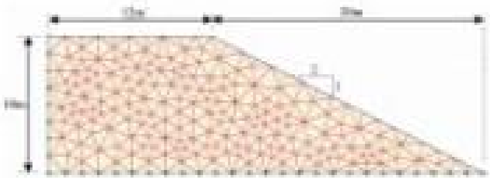


No difference in results for Method 1 and 2

(1) Homogeneous slope with no foundation layer

FEM

Geometry and mesh:



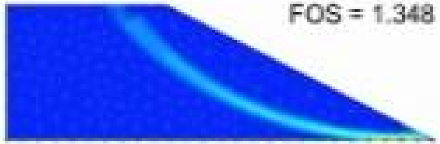
Soil parameters with Mohr-Coulomb model:

Description	Symbol	Unit	Value
Unit weight	γ	[kN/m³]	20
Effective secant modulus	E'	[kPa]	100.000
Effective poisson's ratio	ν'	[-]	0.3
Cohesion (effective shear strength)	c'	[kPa]	10
Friction angle (effective shear strength)	ϕ'	[°]	20

Failure mechanism:

Incremental strains:

FOS = 1.348



Incremental displacement:

Advantage of FEM vs. LEM for Slope Stability Analysis

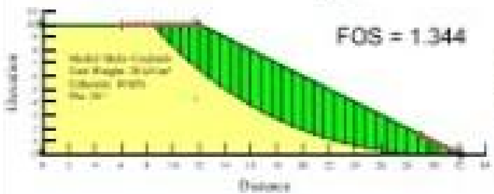
1. In the **FEM**, failure occurs naturally through the zones within the soil mass wherein the shear strength of the soil is not capable to resist the applied shear stress, so there is **no need to make assumption about the shape or location of the failure surface**.
2. There is no theory of slices in the **FEM**, so **no need to make assumption about slide side forces**. The FEM maintains overall equilibrium until failure is reached.
3. As long as the compressibility data of soils is available, the **FEM** will **provide deformations** result at the working stress levels.
4. The **FEM** is capable to check **the progressive failure** up to and including shear failure.

Source: Griffiths and Lane, Slope stability analysis by finite elements, Geotechnique 49, 387-403, 1999

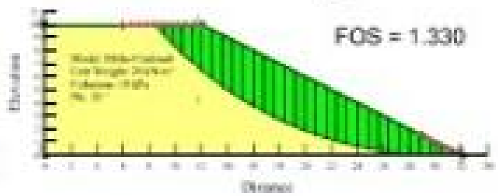
(1) Homogeneous slope with no foundation layer

LEM

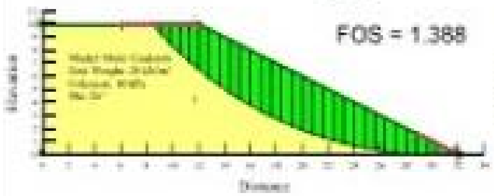
Ordinary Method of Slice:



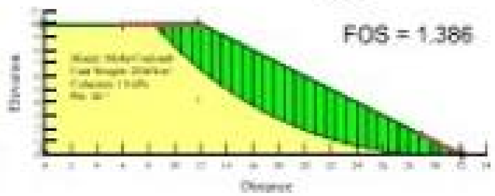
Janbu's Simplified Method :



Bishop's Simplified Method :



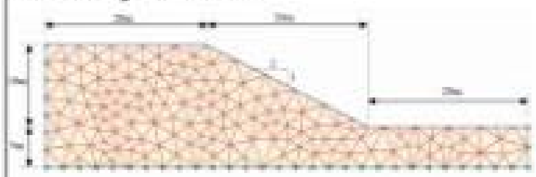
Morgenstern and Price Method :



(2) Homogeneous slope with foundation layer

FEM

Geometry and mesh:



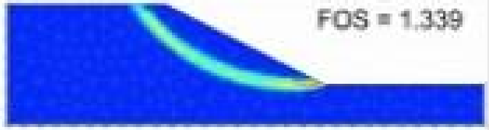
Soil parameters with Mohr-Coulomb model:

Description	Symbol	Unit	Value
Unit weight	γ	[kN/m³]	20
Effective secant modulus	E'	[kPa]	100.000
Effective poisson's ratio	ν'	[-]	0.3
Cohesion (effective shear strength)	c'	[kPa]	10
Friction angle (effective shear strength)	ϕ'	[°]	20

Failure mechanism:

Incremental strains:

FOS = 1.339

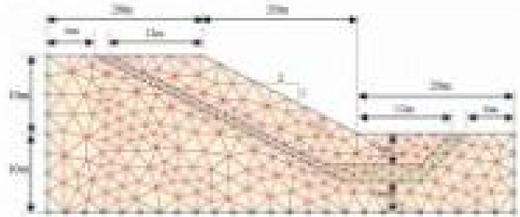


Incremental displacement:

(3) An Undrained Clay Slope with a Thin Weak Layer

FEM

Geometry and mesh:



Soil parameters with Mohr-Coulomb model:

Description	Symbol	Unit	Value
Unit weight	γ	[kN/m³]	20
Effective secant modulus	E'	[kPa]	100.000
Effective poisson's ratio	ν'	[-]	0.3
Cohesion (undrained shear strength)	c_u	[kPa]	50
Friction angle (undrained shear strength)	ϕ_u	[°]	0

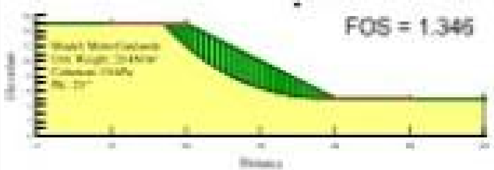
The analysis are carried out using a constant value of undrained shear strength of soil (cu_1) and five different values of undrained shear strength of the thin layer (cu_2) with ratio cu_2/cu_1 equal to **1**, **0.8**, **0.6**, **0.4**, and **0.2**.

(2) Homogeneous slope with foundation layer

LEM

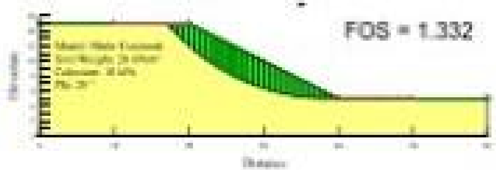
Ordinary Method of Slice:

FOS = 1.346



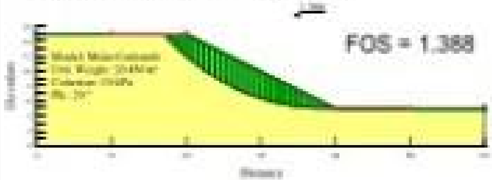
Janbu's Simplified Method :

FOS = 1.332



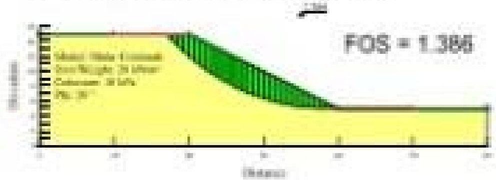
Bishop's Simplified Method :

FOS = 1.388



Morgenstern and Price Method :

FOS = 1.386



(3) An Undrained Clay Slope with a Thin Weak Layer

FEM

Failure mechanism (incremental strains):

c_{u2}/c_{u1} = **1.0**
FOS = 1.451

c_{u2}/c_{u1} = **0.8**
FOS = 1.424

c_{u2}/c_{u1} = **0.6**
FOS = 1.366

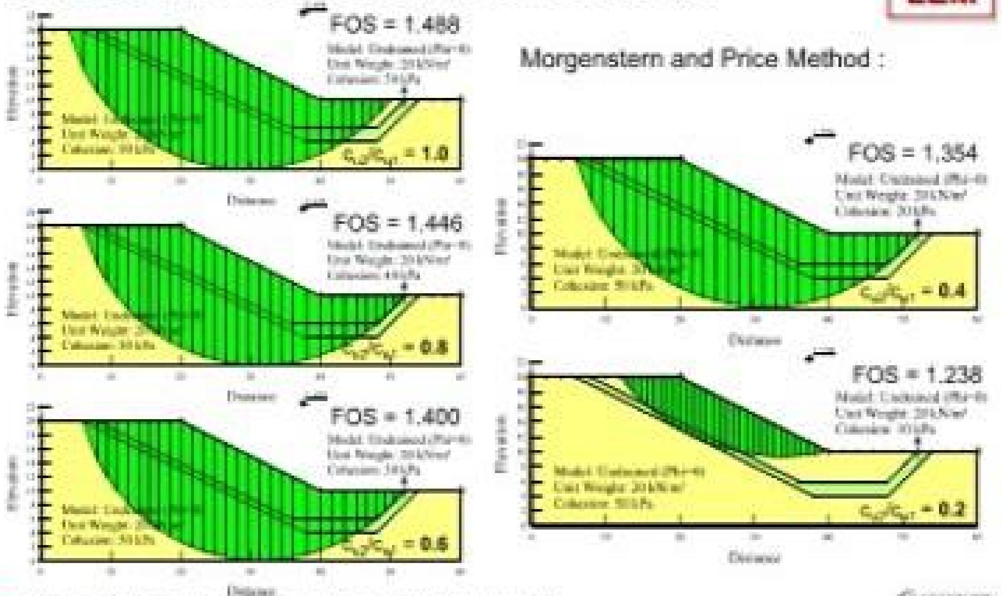
c_{u2}/c_{u1} = **0.4**
FOS = 0.954

c_{u2}/c_{u1} = **0.2**
FOS = 0.505

(3) An Undrained Clay Slope with a Thin Weak Layer

LEM

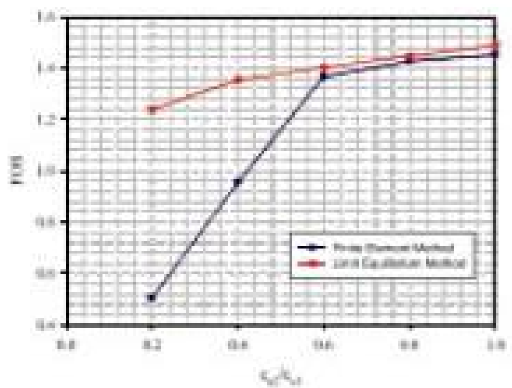
Morgenstern and Price Method :



(3) An Undrained Clay Slope with a Thin Weak Layer

Computed FOS for an undrained clay slope with a thin weak layer with variations of c_{u2}/c_{u1}:

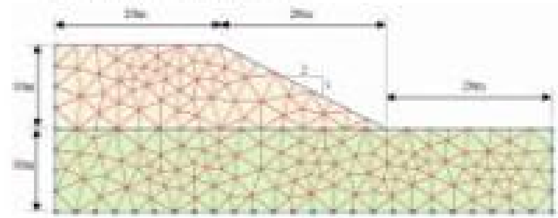
FEM vs. **LEM**



(4) An Undrained Clay Slope with a Weak Foundation Layer

FEM

Geometry and mesh:



Soil parameters with Mohr-Coulomb model:

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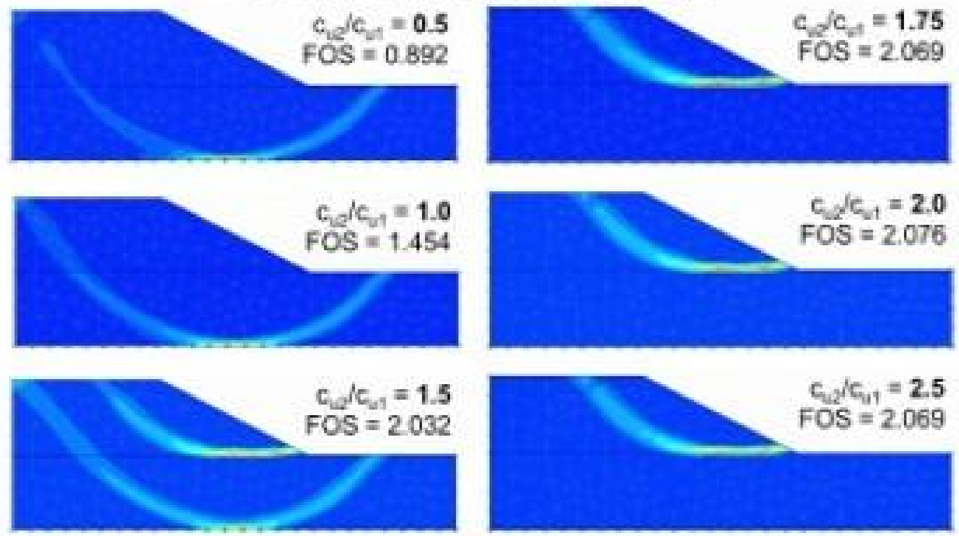
Cohesion (undrained shear strength)	c_{u1}	[kPa]	50
Friction angle (undrained shear strength)	ϕ_u	[°]	0

The analysis are carried out using a constant value of undrained shear strength of soil (cu_1) and six different values of undrained shear strength of the foundation layer (cu_2) with ratio cu_2/cu_1 equal to **0.5**, **1.0**, **1.5**, **1.75**, **2.0** and **2.5**.

(4) An Undrained Clay Slope with a Weak Foundation Layer

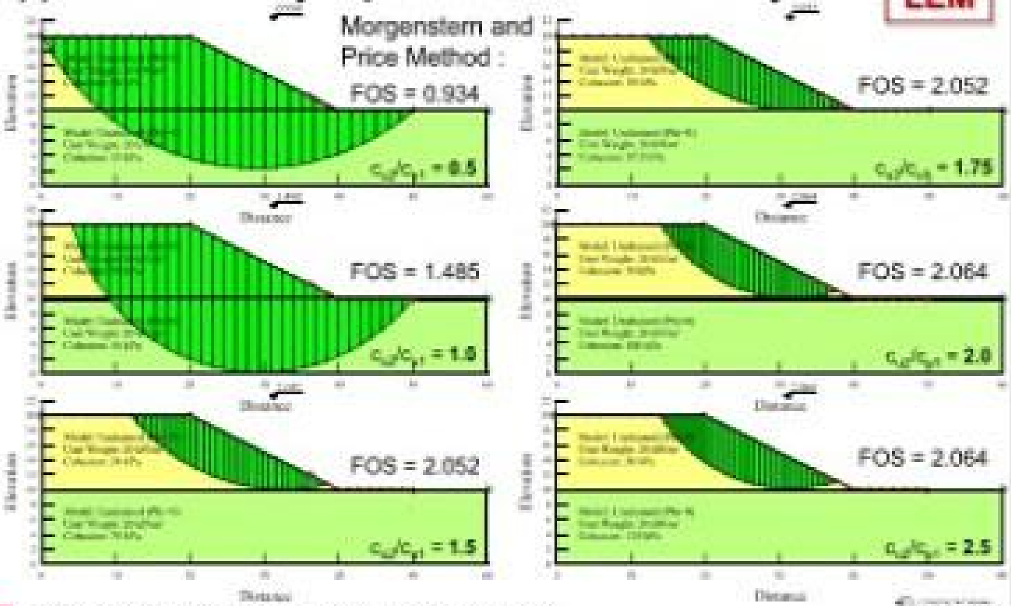
FEM

Failure mechanism (incremental strains):



(4) An Undrained Clay Slope with a Weak Foundation Layer

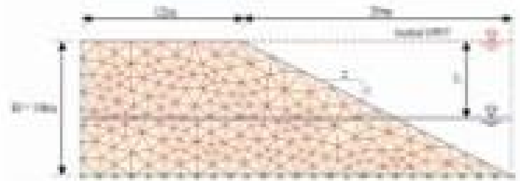
LEM



(5) Homogeneous Slope with Horizontal Free-Surface

FEM

Geometry and mesh:



Soil parameters with Mohr-Coulomb model:

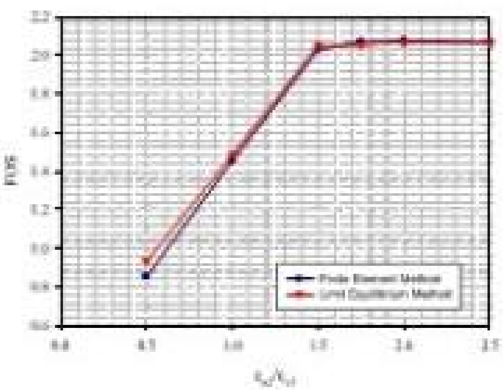
Description	Symbol	Unit	Value
Unit weight	γ	[kN/m³]	20
Effective secant modulus	E'	[kPa]	100,000
Effective poisson's ratio	ν'	[-]	0.3
Cohesion (effective shear strength)	c'	[kPa]	10
Friction angle (effective shear strength)	ϕ'	[°]	20

In this analysis, a slope with different drawdown ratio, L/H which has been varied from 0.0 (slope completely submerged with water level at the crest of the slope) to 1.0 (water level at the toe of the slope) were considered

(4) An Undrained Clay Slope with a Weak Foundation Layer

Computed FOS for an undrained clay slope with a weak foundation layer with variations of c_{u2}/c_{u1}:

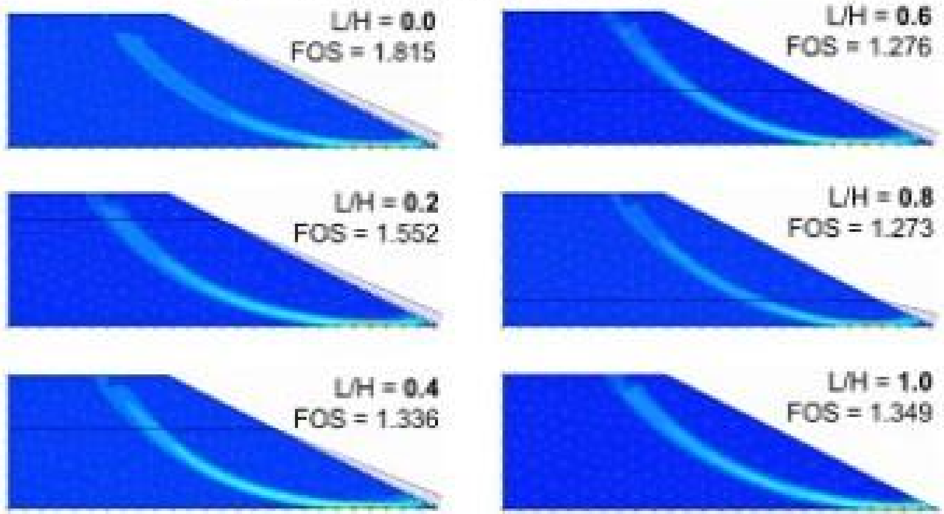
FEM vs. **LEM**



(5) Homogeneous Slope with Horizontal Free-Surface

FEM

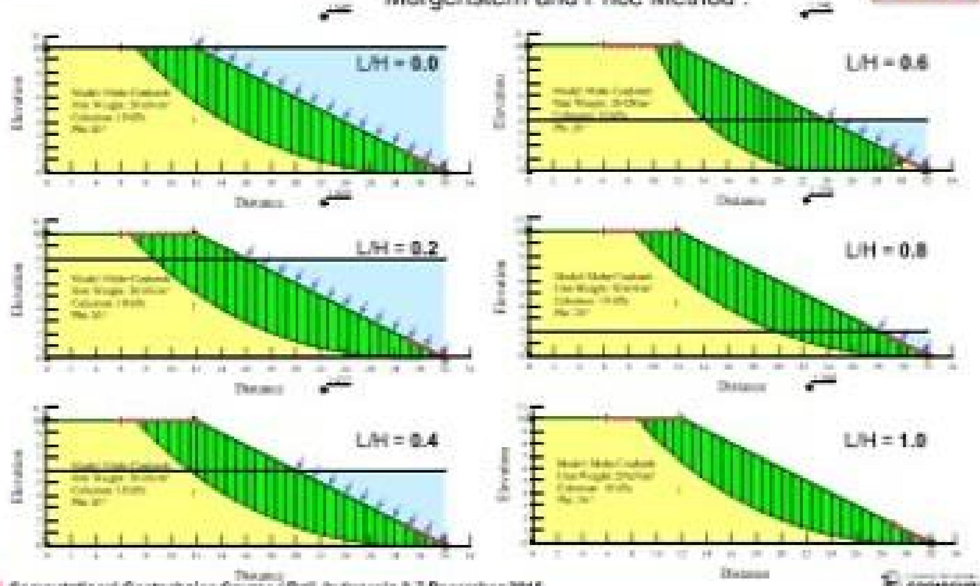
Failure mechanism (incremental strains):



(5) Homogeneous Slope with Horizontal Free-Surface

LEM

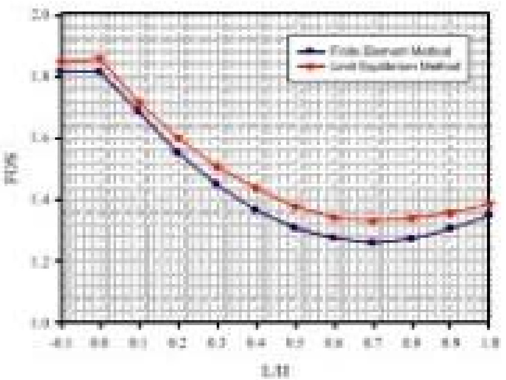
Morgenstern and Price Method :



(5) Homogeneous Slope with Horizontal Free-Surface

Computed FOS for homogeneous slope with horizontal free-surface with variations of L/H:

FEM vs. **LEM**



Unsaturated soil slope subjected to rainfall infiltration

In slope stability analysis, the effect of negative pore water pressure or suction is usually not taken into account because suction will reduce with rainfall infiltration and therefore it can be assumed that matric suction does not influence the long term stability of the slope.

However, to reduce matric suction from the soil, the rainfall needs to be sustained over a significant time period and also the rainfall intensity needs to approximate the saturated coefficient of permeability of the soil at the ground surface.

Hydraulic characteristics such as saturated coefficient of permeability and initial degree of saturation, intensity and duration of rainfall are parameters which are important in the analysis of slope stability considering rain infiltration.

According to Biot's theory of consolidation, to analyze the behaviour of unsaturated soils, is required to simultaneously compute deformation and groundwater flow with time dependent boundary conditions (fully coupled flow deformation analysis).

Hydraulic Models

Van Genuchten (1980) presented a set of closed-form equations of hydraulic characteristics for unsaturated soils which is based on the capillary model of Mualem (1976). The Van Genuchten model introduced the relation between saturation and suction pore pressure head (ϕ_p):

$$S(\phi_p) = S_{residu} + (S_{sat} - S_{residu})\left[1 + \left(g_a \left|\phi_p\right|\right)^{g_n}\right]^{g_c}$$

$$\phi_p = -\frac{u_w}{\rho_w g}$$

where S_{residu} is the residual degree saturation of the soil that describes the part of water that remains in the soil even at high suction heads. S_{sat} is the degree saturation of the soil when the pores are filled with water. g_a, g_n and g_c are empirical parameters, and it is assumed that:

$$g_c = \frac{1 - g_n}{g_n}$$

Hydraulic Models

The Van Genuchten Model is used in which the effective degree of saturation (S_e) is obtained as:

$$S_e=\frac{S-S_{residu}}{S_{sat}-S_{residu}}$$

The relative permeability in relation to Mualem – Van Genuchten is:

$$k_{rel}(S)=(S_e)^{g_l}\left[1-\left(1-S_e^{\frac{g_n}{g_n-1}}\right)^{\frac{g_n-1}{g_n}}\right]^2$$

where g_l is an empirical parameter.

Oberg and Sallfors (1997) and Vanapalli et al. (1996) suggested that the factor χ can approximately be replaced by the degree of saturation or the effective degree of saturation, because the shear strength of unsaturated soils is strongly related to the amount of water in voids of soils and in turn to the matric suction.

Consequently, the effective stress equation can be simplified to:

$$\sigma' = \sigma - S\,u_w$$

where S is the degree saturation of the soil.

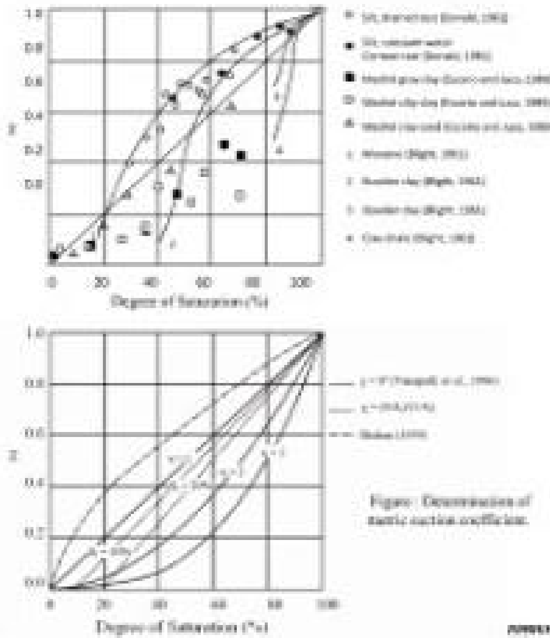


Figure : Determination of matric suction coefficient.

Shear Strength of Unsaturated Soil

The principle of effective stress is applicable for saturated soils. For unsaturated soils, the water phase fills only parts of the pore volume, whereas the remainder is occupied by air. Bishop (1959) has modified Terzaghi's classical effective stress theory and presented the matric suction coefficient (χ) for the effective stress of unsaturated soils:

$$\sigma' = (\sigma - u_a) + \chi\,(u_a - u_w)$$

where σ' and σ are the effective and total stress respectively, u_a is the pore air pressure, and u_w is pore water pressure. The term ($u_a - u_w$) is called matric suction and χ is the matric suction coefficient and varies from 0 to 1 covering the range from dry to fully saturated conditions.

By assuming that the pore air pressure is constant and is small enough to be neglected (u_a = 0), consequently for a dry soil, effective stress and total stress are the same. The matric suction coefficient (χ) is usually obtained from laboratory tests on both saturated and unsaturated samples.

Matric Suction Profile

The matric suction profile will come to equilibrium at a hydrostatic condition when there is a zero net flux from the ground surface. If moisture is extracted from the ground surface such as evaporation, the matric suction profile will be drawn to the left. If moisture enters at the groundwater surface such as infiltration, the matric suction profile will be drawn to the right.

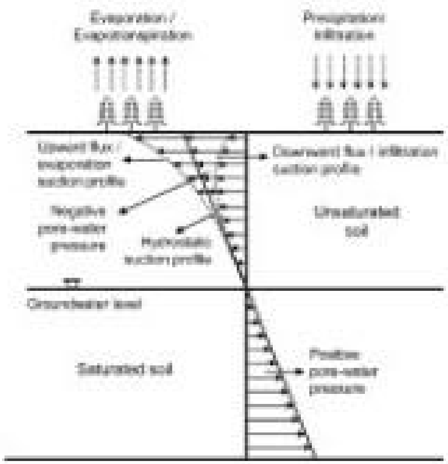


Figure : Matric suction profile in horizontally layered unsaturated soil profiles

Example of Unsaturated Soil Slope

In this part slope stability analysis of unsaturated soils due to rain infiltration will be discussed. A simple case of a homogeneous slope has been chosen. The international soil classification system USDA series is used for determining the hydraulic data for the analysis. The mechanical and hydraulic models used in the analysis are the Mohr Coulomb failure criterion and the Van Genuchten model respectively. The height of the slope is 10 m and the gradient (horizontal to vertical) is 2:1.

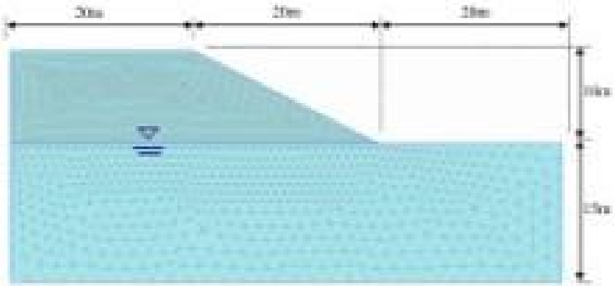


Figure : Geometry and two dimensional finite element mesh (4000 15-noded elements)

Hydraulic Parameters

Four different hydraulic parameter sets of the USDA series for the Van Genuchten Models are used to evaluate the effect of these parameters in slope stability during rain infiltration:

Texture	K_{sat} (m/s)	g_a (1/m)	g_n (-)	g_l (-)
Sand	8.25E-05	14.50	2.68	0.50
Loamy Sand	4.05E-05	12.40	2.28	0.50
Sandy Loam	1.23E-05	7.50	1.89	0.50
Loam	2.89E-06	3.60	1.56	0.50
Silt	6.94E-06	1.60	1.37	0.50
Silty Loam	1.25E-06	2.00	1.41	0.50
Sandy Clay Loam	3.63E-06	5.90	1.48	0.50
Clayey Loam	7.22E-06	1.90	1.31	0.50
Silty Clay Loam	1.94E-06	1.00	1.23	0.50
Sandy Clay	3.33E-06	2.70	1.23	0.50
Silty Clay	5.56E-07	0.50	1.09	0.50
Clay	5.56E-06	0.80	1.09	0.50

Source : Plaxis 2D Reference Manual 2010 Beta

Soil Parameters

Soil parameters for the Mohr Coulomb model used in the analysis:

Description	Symbol	Unit	Value
Unit weight	γ	kN/m³	20
Elasticity modulus	E'	kPa	7500
Effective poisson's ratio	ν'	-	0.35
Effective cohesion	c'	kPa	20
Effective friction angle	ϕ'	°	20

Boundary Conditions

The initial ground water level was assumed to be horizontal at level of the toe of the slope. A rainfall with intensity of 10 mm/hour lasting 3 days (72 hours) was applied on the crest and the slope. The minimum and the maximum pore pressure head respectively are -0.1 m (θ_{min}) and 0.1m (θ_{max}). The left boundary, right boundary and lower boundary of the model were assumed impervious boundaries.

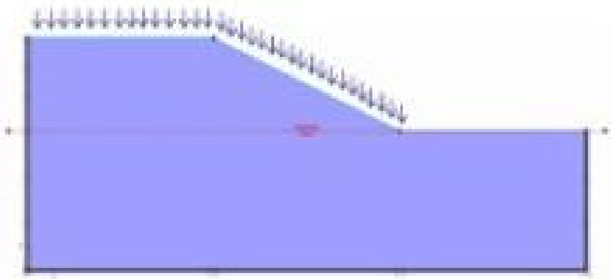


Figure : Boundary conditions of the model.

Initial Degree of Saturation

Initial degree of saturation for the four different hydraulic parameters leading to different initial degree of saturation at the same suction:

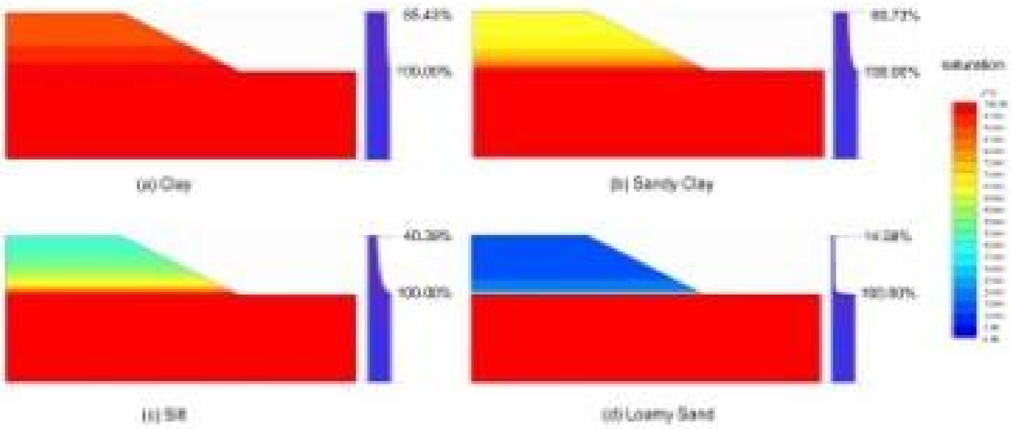


Figure : Initial conditions: degree of saturation.

Initial Suction

Initial suction in the model is assumed to increase linearly above ground water level until ground surface.

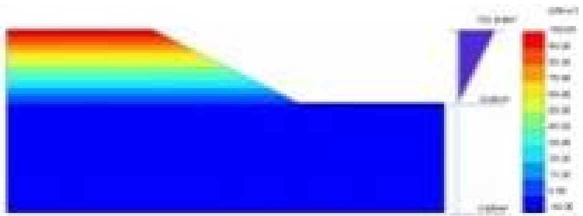


Figure : Initial conditions: suction.

The relation between suction and saturation, i.e. the Soil Water Characteristic Curve (SWCC):

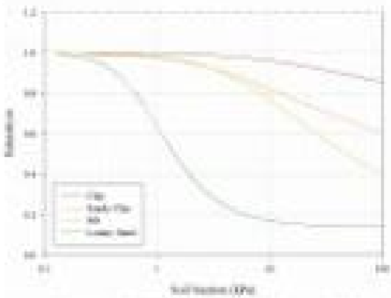


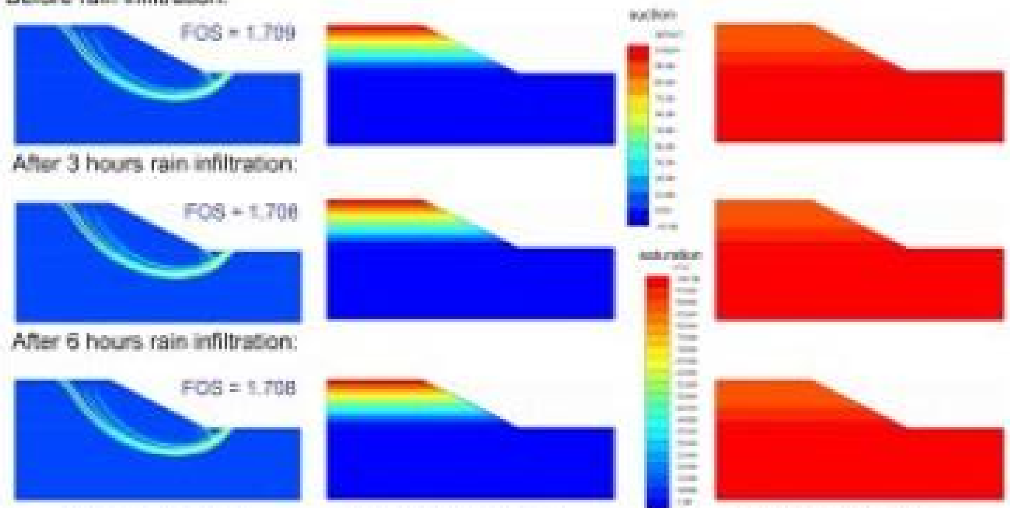
Figure : Soil Water Characteristic Curve (SWCC)

Result: Failure mechanism, distribution of suction and degree of saturation (Clay)

Before rain infiltration:

After 3 hours rain infiltration:

After 6 hours rain infiltration:



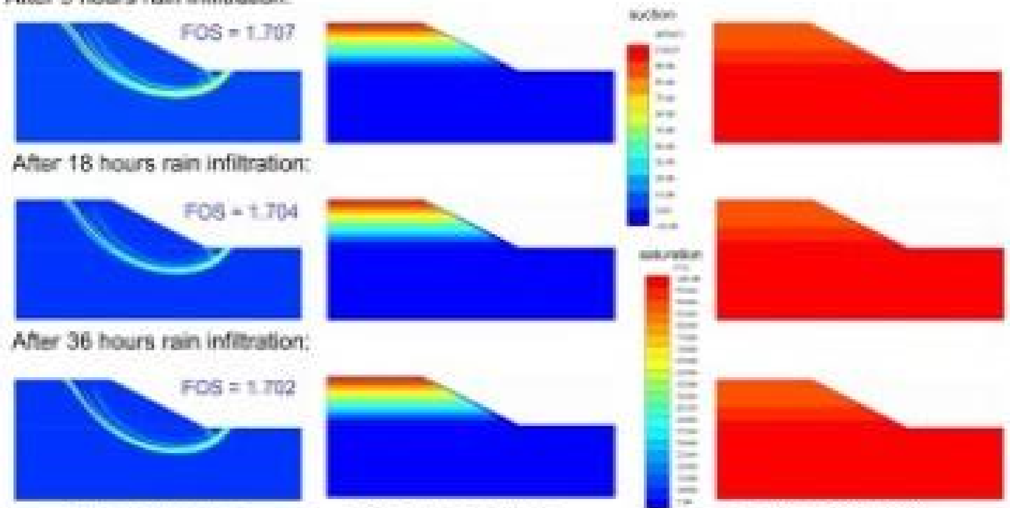
Failure mechanism | Distribution of suction | Degree of saturation

Result: Failure mechanism, distribution of suction and degree of saturation (Clay)

After 9 hours rain infiltration:

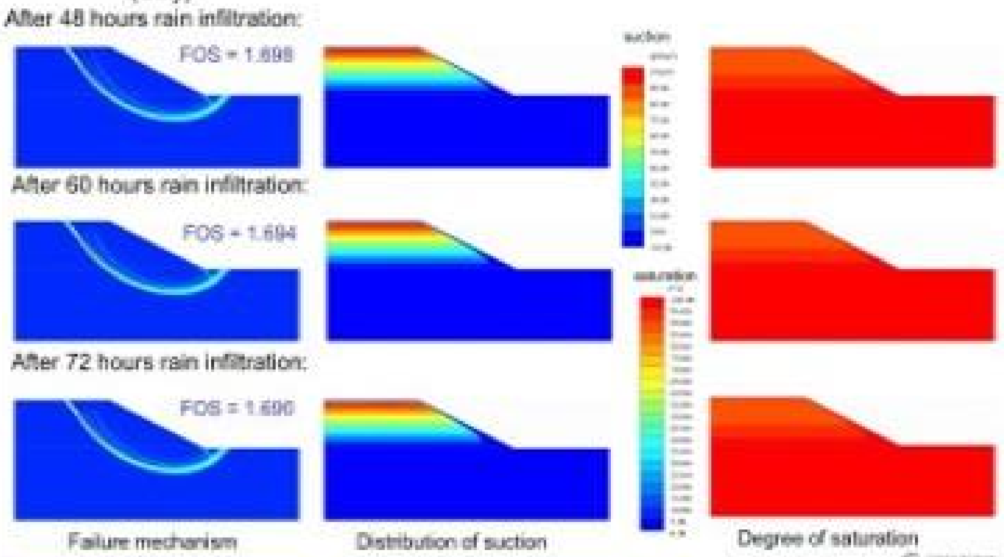
After 18 hours rain infiltration:

After 36 hours rain infiltration:

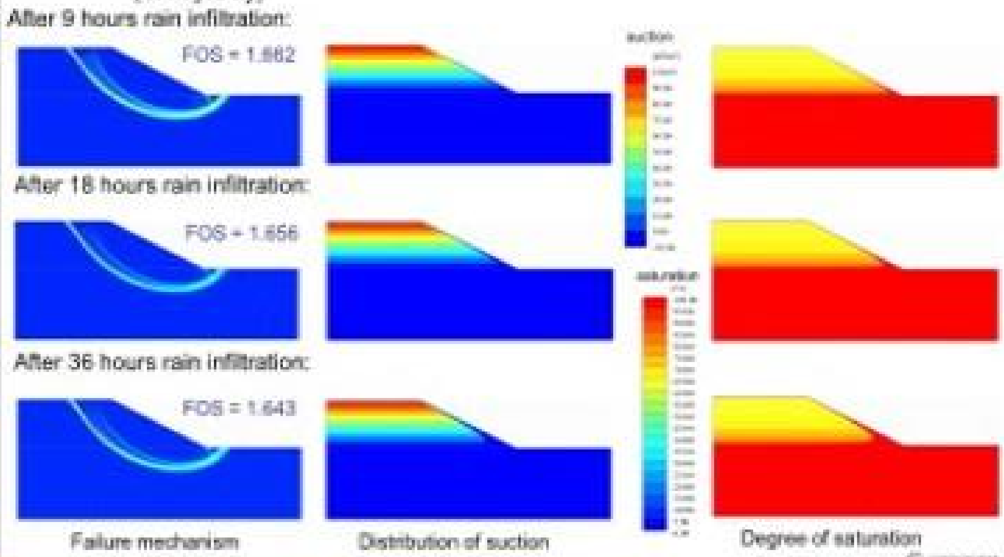


Failure mechanism | Distribution of suction | Degree of saturation

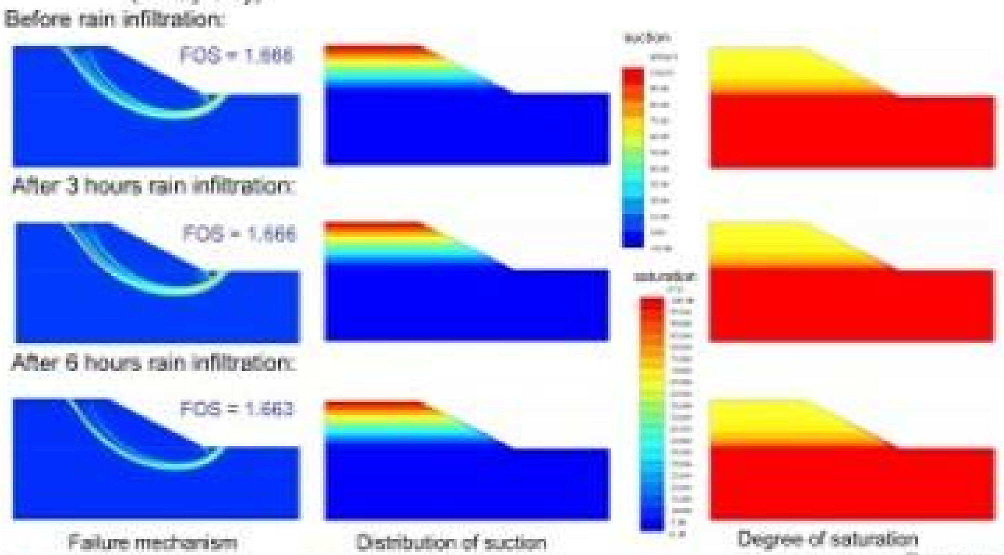
Result: Failure mechanism, distribution of suction and degree of saturation (Clay)



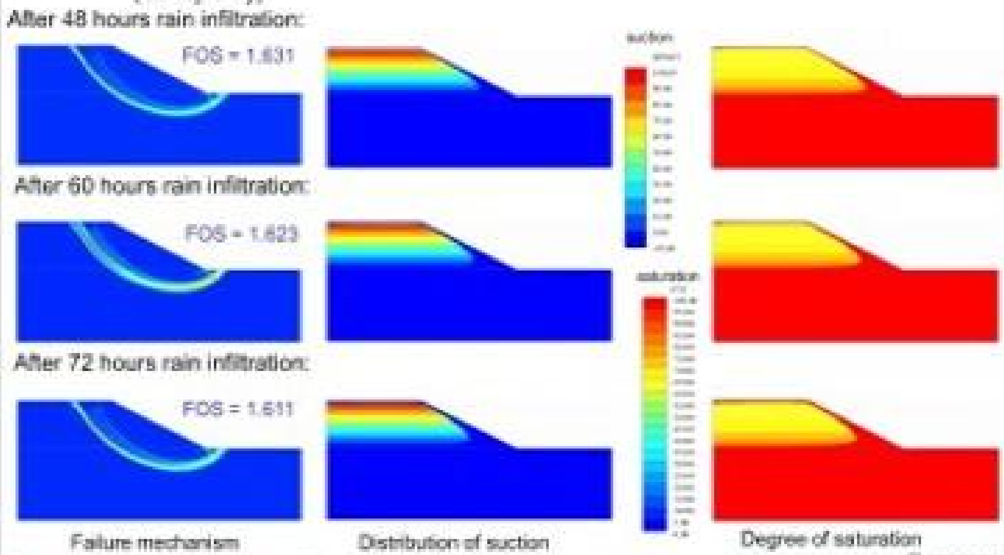
Result: Failure mechanism, distribution of suction and degree of saturation (Sandy Clay)



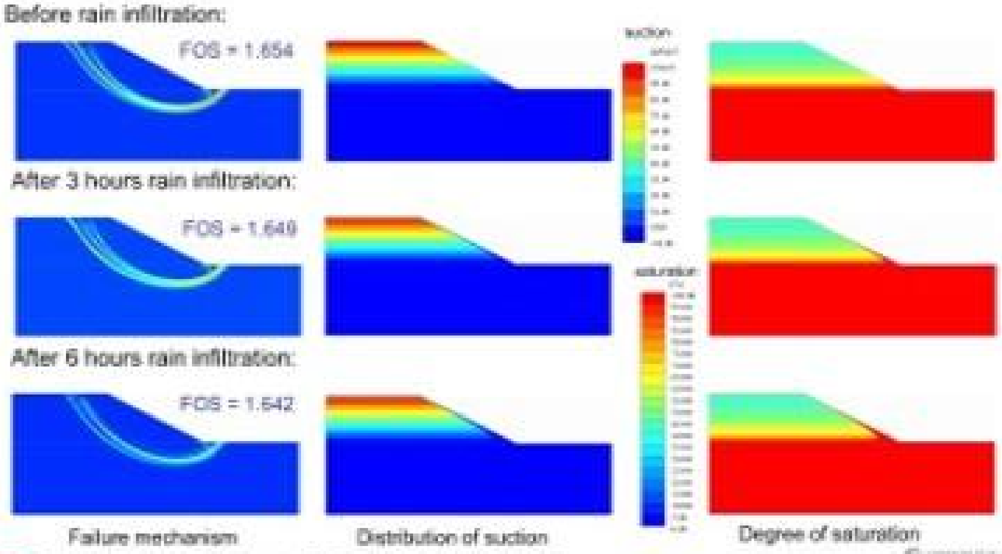
Result: Failure mechanism, distribution of suction and degree of saturation (Sandy Clay)



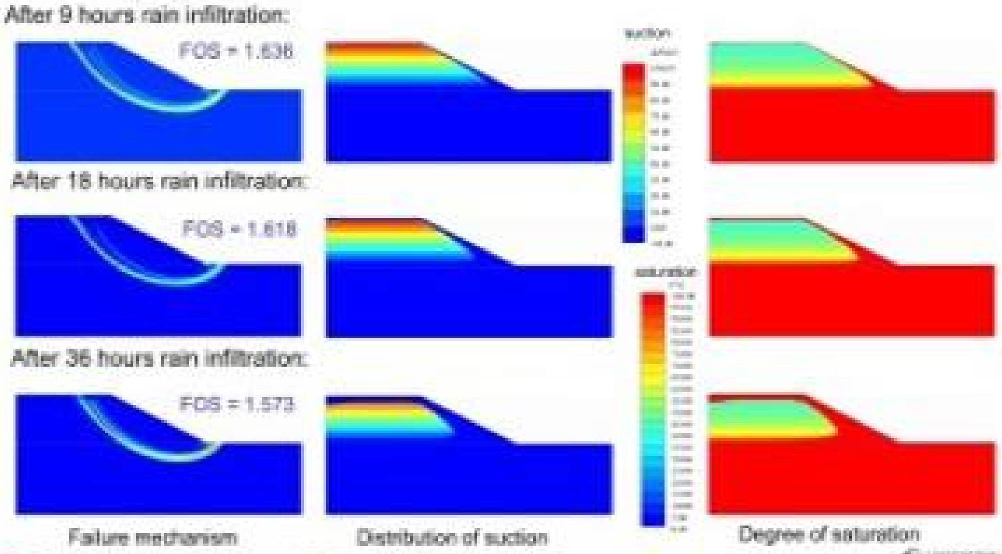
Result: Failure mechanism, distribution of suction and degree of saturation (Sandy Clay)



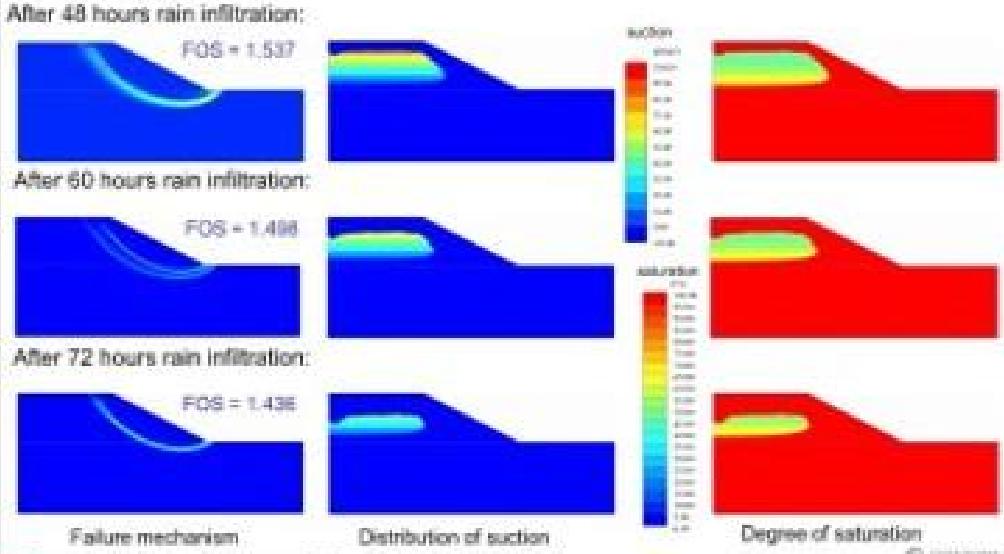
Result: Failure mechanism, distribution of suction and degree of saturation (Silt)



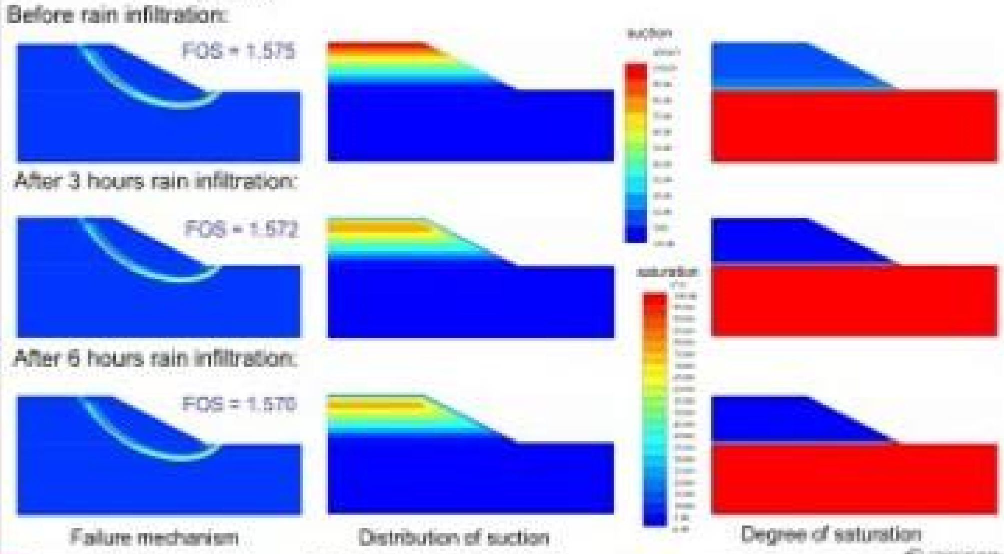
Result: Failure mechanism, distribution of suction and degree of saturation (Silt)



Result: Failure mechanism, distribution of suction and degree of saturation (Silt)



Result: Failure mechanism, distribution of suction and degree of saturation (Loamy Sand)

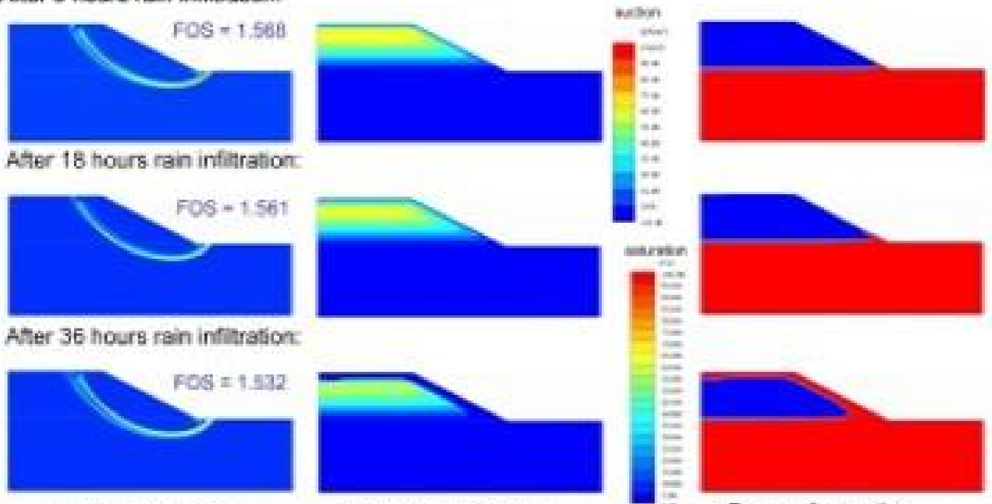


Result: Failure mechanism, distribution of suction and degree of saturation (Loamy Sand)

After 9 hours rain infiltration:

After 18 hours rain infiltration:

After 36 hours rain infiltration:



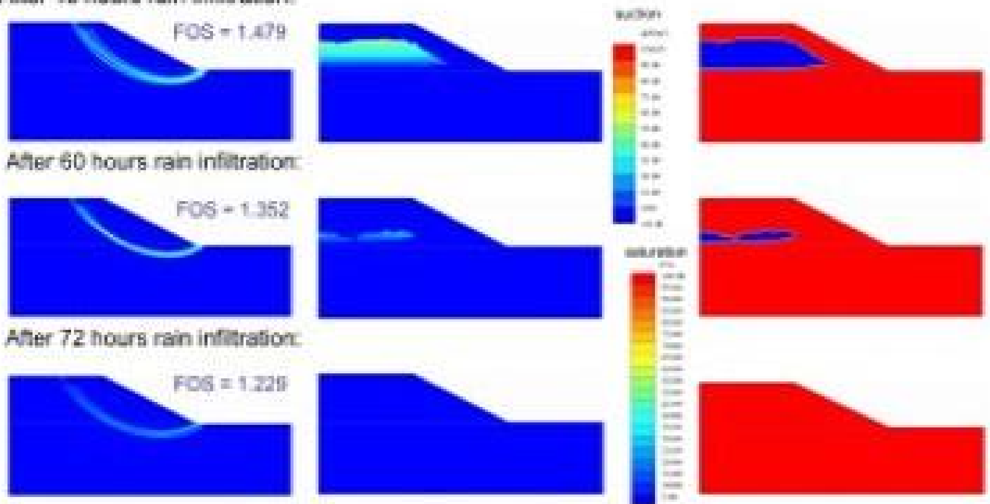
Failure mechanism   Distribution of suction   Degree of saturation

Result: Failure mechanism, distribution of suction and degree of saturation (Loamy Sand)

After 48 hours rain infiltration:

After 60 hours rain infiltration:

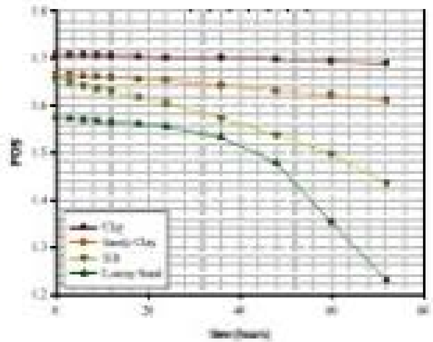
After 72 hours rain infiltration:



Failure mechanism   Distribution of suction   Degree of saturation

Resume of FOS of unsaturated soil slope during rain infiltration:

Time (hours)	FOS			
	Clay	Sandy Clay	Silt	Loamy Sand
0	1.709	1.668	1.654	1.575
3	1.708	1.666	1.649	1.572
6	1.708	1.663	1.642	1.570
9	1.707	1.662	1.636	1.568
12	1.706	1.660	1.631	1.565
18	1.704	1.658	1.618	1.561
24	1.702	1.653	1.606	1.556
36	1.702	1.643	1.573	1.532
48	1.698	1.631	1.537	1.479
60	1.694	1.623	1.498	1.352
72	1.690	1.611	1.436	1.229



Conclusions

- Safety factors from FEM compare well with factors obtained from LEM.
- FEM for slope stability is more powerful than LEM. The failure mechanisms in FEM are computed automatically as part of the stress equilibrium process.
- Effect of rainfall infiltration, leading to change of suction and saturation in slope, on factor of safety can be assessed.
- During the time of rain infiltration, suction decreases and thus the FOS of the slope reduces, whereas the reduction is faster for soils with high permeability than for soils with low permeability.