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Mechanism and modelling of shallow soil slope stability during high intensity and short duration rainfall

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Matric;
Osmotic and total suctions;
Unsaturated soil's shear strength.

Abstract Shallow landslides in nearly saturated uncohesive to slightly cohesive soils are triggered by high intensity, short duration rainfall which infiltrates into soil and changes intergranular friction and effective stresses. For this, the especially developed Soil–Water Interaction Modelling System (SWIMS) was used with CL-ML type soils. For simplicity, rainfall intensity and duration were kept constant. Results showed that (1) All 35° slopes were failed by translational failure. For the other (15°, 25°) slopes, no failures were observed; (2) For all slopes, FOS increased with increasing compaction degree and decreased with increasing slope angle; (3) Other parameters, such as soil density, porosity, saturation degree, water contents, and water permeability may also affect shear strength/slope stability, especially for low degrees of saturation ($S < 95\%$), compared to high degrees of saturation ($S =, > 95\%$). (4) A correlation of SWIMS tests observed that average wetting band depths (h_{obser}), with the calculated wetting band depths from the Lump Equation (h_{LE}), were poor, as h_{obser} values were much higher than h_{LE} values. Differences increased for very low degrees of saturation (S), compared to $S > 95\%$. This meant that the Lump equation underestimated wetting band depths. Further, if the Lump equation is still considered valid, this would imply either water-permeability increases, porosity decreases or both occur towards full saturation; a process where the last possibility is the most probable occurrence.

1. Introduction

Slope stability problems of shallow landslides are among the most commonly encountered problems in geotechnical engineering. Due to the practical importance of the subject, assessing the stability of a natural or man-made slope has received great attention across the geotechnical community, for many decades. The first question that must be answered is: Why does a natural slope suddenly move/fail after a long period of existence? Rainfall effect (intensity, its variation and duration) is one of the most important factors in this question. Slope failures triggered by rainfall cause considerable property damage with loss of life, every year throughout the world. A number of laboratory, numerical and field studies have been conducted to understand interrelations between soil stability and rainfall. A number of landslides in unsaturated soils usually occur during the wet season.

2. Brief background information and scope of work

Most soils occur in an 'unsaturated state' in nature. Unsaturated soil mechanics is a very wide and complex subject, due to the involvement and interaction of 4 phases (pore-air, pore-water, menisci and soil grains) with each other. Shallow landslides are some kind of slope failure that may be induced by rainfall infiltration, which causes some changes in total suction (a sum of matric and osmotic suctions) and in soil properties, such as soil shear strength and pore fluid (air, water, dissolved air in water and menisci) properties, in a process where the mechanism of change (from unsaturation to saturation and back to unsaturation) is yet to be clearly understood. There have been extensive studies done by numerous researchers over the years, both in the field and in the laboratory [1–66]. For soils on

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the dry side of the 'optimum moisture content' of the 'Proctor Curve', the menisci are under tension, separating free air from pore-water and allowing a difference to exist in pressures of pore air and pore water, the value of which is called 'matric suction'. This exists in all kinds of soil: cohesive (in big amounts) or uncohesive (in small amounts). Further, 'osmotic suction' is associated with the double layer theory of clay particles, and is considered to exist only in cohesive soils and not (or considered to be negligible) in uncohesive soils [8]. Thus, for practical purposes, total suction is almost equal to matric suction for CL-ML type slightly cohesive or SP type uncohesive soils, as the osmotic suction component is considered to be negligible for such soils. Total suction affects the shear strength behavior of an unsaturated soil. Thus, for soils on the dry side of the optimum water content, but associated with low degrees of saturation, total suction governs the shear strength behavior of soils. For such unsaturated soils, it is general practice to provide Soil–Water Characteristic Curves (SWCC) or Soil–Water Retention Curves (SWRC), describing relationships between an unsaturated soil moisture content change and its degree of saturation change with its total suction change, which affects its shear strength behavior. When the degrees of saturation near full saturation, menisci disappears, as some air dissolves in the pore water and the remaining air becomes 'occluded' in air bubbles, to move in continuous pore water by the diffusion process. This process is not fully reversible (i.e. pore fluid does not follow the same path during loading and unloading), and hence this causes some hysteresis effects of the pore fluid affecting unsaturated soil behavior [7,8]. On the other hand, the shear strength of unsaturated soils could be studied with respect to the stability of shallow (up to 5 m deep) landslides in the CL-ML type slightly cohesive to uncohesive soils (having effective cohesion, $C' < 10$ Kpa), which are near saturation (i.e. degree of saturation, $S > 95\%$) during and after high intensity ($i > 0.15$ lt/s/m^2) and short duration rainfall ($t < 30$ min) events. A literature review from this perspective can be divided into 4 categories:

(a) General framework information on unsaturated soil behavior and on shallow landslides [6,10,11,24,27,29,32,50,51,53,56,57,63].
(b) Special case studies which could not be generalized in establishing a mechanism of framework behavior to predict the occurrence of similar slides before they occur [28,36,38,58,59,65].
(c) Studies of various unsaturated soils/materials, which relate moisture intake or rainfall infiltration to slope stability or shear strength to suction development, where usually Soil–Water Characteristic Curves (SWCC) or Soil–Water Retention Curves (SWRC) are provided to describe the behavior [1,3,5,9,12–16,18,23,30,31,34,37,40,43–49,54,55,60,61,64,66].
(d) Studies that relate to rainfall infiltration to nearly (or fully) saturated 'wetting band/front' development and its stability [2,4,17,19–22,25,26,33,35,39,41,42,52,62]. Some of these studies give empirical equations calculating wetting depths with or without relating it to rainfall intake [33,41]. Of these, the first reference gives the details of the 'Lump Wetting Band Theory', the validity of which will be checked in this study, as described below.

The principal objective of this research study was two-fold:

1. To develop a small-scale physical slope model called the Soil–Water Interaction Modelling System (SWIMS) in the laboratory to investigate the interrelations between slope stability and rainfall infiltration under laboratory conditions [67], while concentrating on the high degrees of saturation near full saturation (i.e. $0.95 > S > 1.0$), where the final moisture content of the soil is on the wet side of the optimum moisture content, and air is in the 'occluded' phase (in the Standard Proctor test curve-ASTM 698). We were thus able to study total suction effects (i.e. matric suction for our case, since CL-ML, with or without SP type soils, was used) influencing soil shear strength behavior [8]. That is why only a limited number of (i.e. only in SWIMS test:#3) total suction measurements at 5 different locations/depth were undertaken to get one average suction value at any time, t (s), (before starting the main SWIMS test) using soil-tensiometers with high air-entry porous stone tips (Figure 1).
2. To check the validity of the Lump 'Wetting Band' theory [33,41], SWIMS tests were done at high degrees of saturation under high rainfall intensity (for simplicity, kept constant at 0.18 l/s/m^2) and for short duration rainfall (also kept constant at 25 min or 1500 s). Lump's theory describes the movement of the wetting front (i.e. thickness of the wetting band, h_{LE} at any time, t (s)) during any rainfall event by the following equation:

$$h_{LE} = \frac{k^* t}{n^*(S_f - S_i)}, \tag{1}$$

where:

h_{LE}	Thickness of wetting band at any time t (s) after rainfall starts,
k	Permeability of soil (m/s),
t	Elapsed time (s) after rainfall starts (or rainfall duration),
n	Soil porosity,
S_f, S_i	Final and initial degrees of saturation (%).

It is noted that the Lump equation given above does not consider any rainfall intensity, or variation during rainfall, assumes single permeability and porosity values during and after the rainfall (for better correlation final <i.e. at the end of rainfall> values should be used), ignores the presence and variance of menisci properties during rainfall and their influence on water permeability, porosity and shear strength. In this study, a total of 12 model slope (SWIMS) tests were conducted using 2 kinds of soil (CL-ML and CL-ML with 10% medium sand), having different initial and final conditions. Out of these, in only one CL-ML test (i.e. SWIMS test #3), total suction (i.e. matric suctions in our tests) was measured at various (5) locations/depths of the sample to obtain only one average value to be representative of the sample at any time, t (s), during the rainfall event, as described in sections below.

3. Basic laboratory testing

In order to obtain reliable information about the properties of the soil to be used in the model slope (SWIMS) tests, a comprehensive preliminary study was done. First of all, some basic laboratory tests were done (i.e. Particle Size Distribution, Atterberg Limits and Proctor Compaction) and then the soil classification symbol was identified, in accordance with the

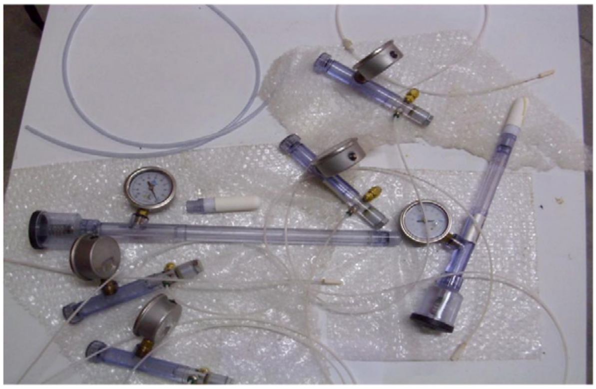

Figure 1: Dial-gauge type soil tensiometers used in the (matric) suction measurements.

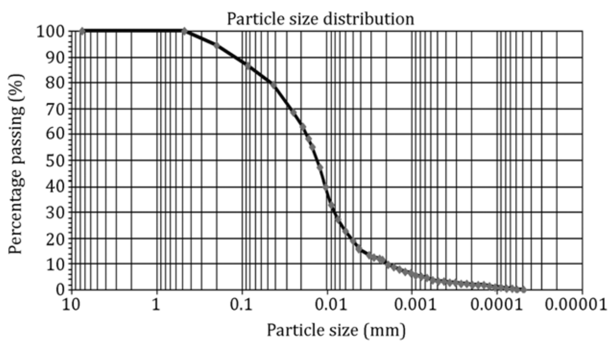

Figure 2: Particle size distribution graph [67].

Unified Soil Classification System (USCS). Several test methods were used to determine the particle size distribution curve (Figure 2). For this project, a wet sieve analysis was used for the coarse soils part, while hydrometer and laser diffraction tests were used for the fine soil fraction. Mostly, ASTM Standards were used.

Another significant variable in this study is the initial water content of the soil. Soil behavior is highly dependent on its initial water content (w_c) and initial degree of saturation. In order to examine the effect of initial water content on the slope stability, two different initial water contents (14% and 30%) are prepared before compaction takes place. The assessment, in which the initial water content value is to be used, depends upon the optimum moisture content of the soil, found from the Standard Proctor Test curve (ASTM D 698), shown in Figure 3. The right side of the peak point of the curve is called the 'wet side' which covers higher water content than the optimum moisture content with softer sample consistency. The dry (left) side of the optimum water content has lower water content than the 'optimum' with stiffer consistency.

Table 1 summarizes some basic soil mechanics laboratory tests performed in this study.

Soil density is another variable affecting soil slope stability. Compaction is the process by which soil particles are closely packed by mechanical means, thus increasing their dry density. Dry unit weight, here is defined as the ratio of the weight of soil particles to the soil total volume. Soils are made up of soil grains with voids filled with air and water. Compaction only decreases the air in the voids. It has no effect on the solid volume and on the water content. Shear strength, compressibility and permeability are fundamental engineering characteristics of a soil. Compaction of a soil generally increases its shear

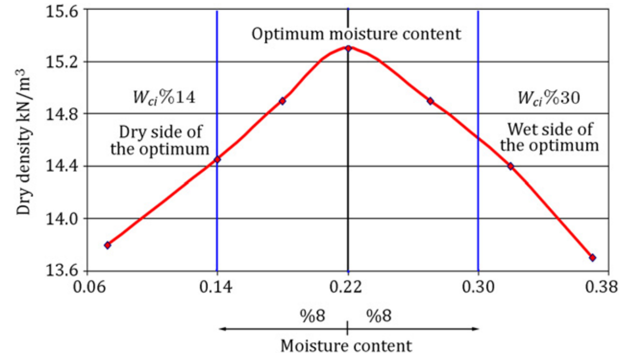

Figure 3: Standard proctor compaction test results [67].

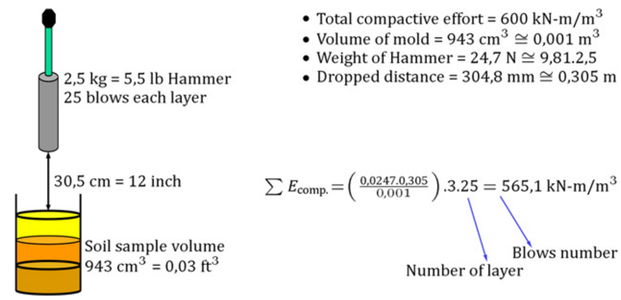

Figure 4: Standard proctor test details [67].

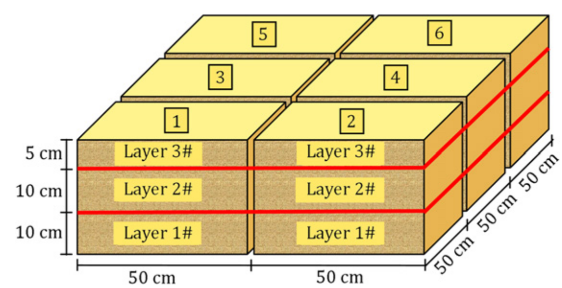

Figure 5: Compaction layer dimensions [67].

strength, due to increasing inter-granular friction, decreases its void ratio, porosity, compressibility and its (air and water) permeability. Two different soil densities are used in the model slope (SWIMS) tests. In order to obtain a uniform and homogeneous soil mass, a specific compaction method, based on the Standard Proctor Test (ASTM D 698), was used. Figures 4 and 5 summarize how the model slope compaction procedure was achieved.

Compaction of the soil sample was obtained, using three layers, each with 10 or 25 hammer blows. To find the needed total compaction energy, firstly the energy that can be provided from a single hammer-stroke is calculated. As indicated in the ASTM D 698—Standard Proctor Compaction Test, the volume of the mold is 943 cm^3, which equals approximately 0.001 m^3. Further, using the standard proctor test hammer, a rigid plate with dimensions of 500, 500 and 20 mm was utilized to provide its area compaction uniformly. As there are 6 areas to be compacted, the procedure was repeated 6 times. Figure 5 shows the details of the compaction process.

In order to obtain two different soil densities, two different numbers of stroke (i.e. 10 and 25 blows per layer) were used. Figure 6 shows the SWIMS equipment parts before placing and

Table 1: Summary of the laboratory test results of the SWIMS soils [67].

No	Experiment name	Used method	ASTM-D	Value	Unit
1	Particle size analysis	Wet sieve analysis	ASTM-D 422-63	Grading curve (Figure 1)	(%)
2	The laboratory compaction test	Standard proctor method	ASTM-D 698-00	$W_{opt=22}$	(%)
				$\gamma_{dry\ max} = 15.3$	kN/m^3
3	Classification of soil	USCS	ASTM-D 2487-00	CL & ML	–
4	Triaxial compression test	Consolidated Undrained (CU)	ASTM-D 4767-04	$c' = 9\ \phi' = 30$	kPa (°)
5	Direct shear test	Consolidated Drained (CD)	ASTM-D 3080-00	$c' = 9\ \phi' = 34$	kPa (°)
6	Liquid limit test	Casagrande method	ASTM-D 4318-00	47	(%)
7	Plastic limit test	Hand method	ASTM-D 4318-00	32	(%)

Table 2: Summary of runoff, absorbed and infiltrated water obtained at each SWIMS test [67].

No	Angle of slope (°)	Number of blows	Initial W_c (%)	Total (lt.) water Q_T	Runoff water (lt.) Q_R	Absorbed water (lt.) Q_M	Infiltrated water (lt.) Q_i
1	15	10	14	400	295.4	32.60	72
2	15	10	30	400	286.96	25.49	87.55
3	15	25	14	400	315.2	32.4	52.4
4	15	25	30	400	307	36	57
5	25	10	14	400	353	47	0
6[a]	25	10	30	400	302	18	80
7	25	25	14	400	361	39	0
8[a]	15	10	30	400	294.5	16.8	80.7
9	35	10	14	400	330	46	24
10	35	10	30	400	364	36	0
11	35	25	14	400	376	24	0
12	35	25	30	400	382	18	0

[a] Soil sample consist of 90% CL-ML and 10% SP.

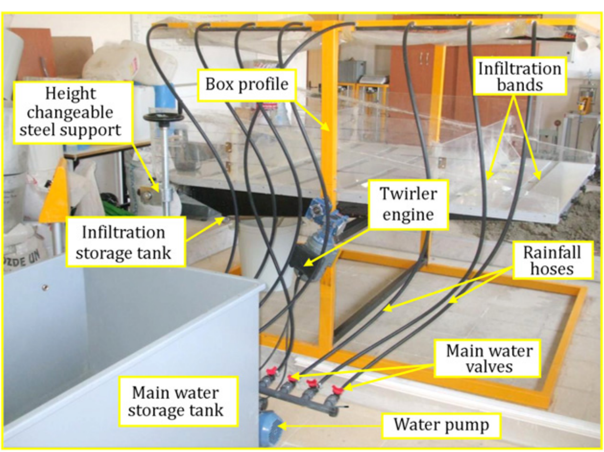

Figure 6: General view of the soil water interaction modeling system-SWIMS [67].

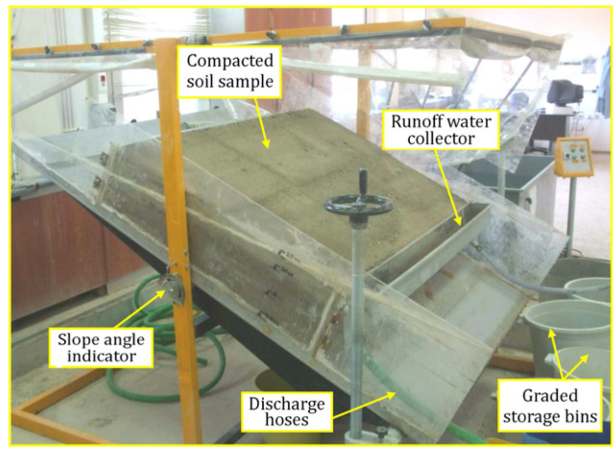

Figure 7: View of the filled SWIMS container and other equipment used [67].

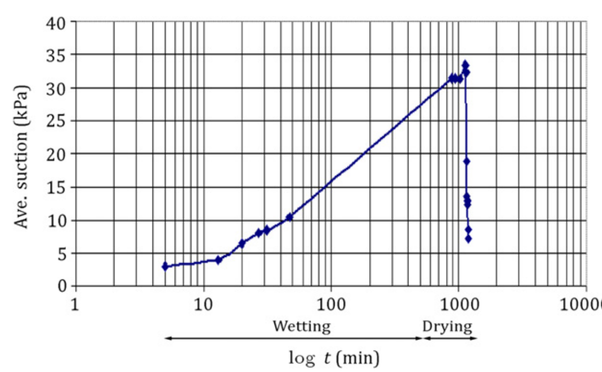

Figure 8: Development of measured average (matric) suction over time.

compacting the soil, while Figure 7 gives the SWIMS test set-up view, with the compacted soil, before rainfall starts.

Twelve model slope (SWIMS) experiments were performed (under İYTE-BAP financial assistance) at the Izmir Institute of Technology (IYTE)'s-Soil Mechanics Laboratory. In these twelve main experiments, three different soil parameters were varied, which were initial moisture contents, soil densities and slope angles (15°–25°–35°). In all tests, the same rainfall intensity (0.18 l/s/m^2) and the same duration (1500 s) were used, while any slope failure and variations of the sample wetting band depths (h_{obser}, taken as average depths of 2 opposite sides) were noted. A summary of SWIMS tests is given in Tables 2 and 3.

Direct measurements of (matric) suctions, using tensiometers, were made in only one replica, SWIMS test #3 sample, prepared later (under Tubitak T1001 financial assistance) with (matric) suction measurements at 5 different locations/depths to obtain one average suction value at any time, t (min), to represent the sample. The amount of rainfall applied was about 10% of the previous amount to allow for suction development (0.02 l/s/m^2) during rainfall means, wetting period and after rainfall means, and drying period. Results of (matric) suction measurements are given in Figure 8, which gives the development of the average of 5 tensiometer measured (matric) suctions (i.e. $u_a - u_w$) over the total monitoring time $t = 1200$ min, including the wetting application time of $t = 720$ min in the SWIMS test set-up, conducted later as a separate experiment using a prepared replica soil sample, properties of which were the same as those in Test 3 of Table 3.

Various records were obtained from SWIMS experiments, such as amounts of surface runoff, water infiltrated into soil, water infiltrated-through soil (passed below the tilted table), absorbed water, free water, infiltration depth, erosions (if

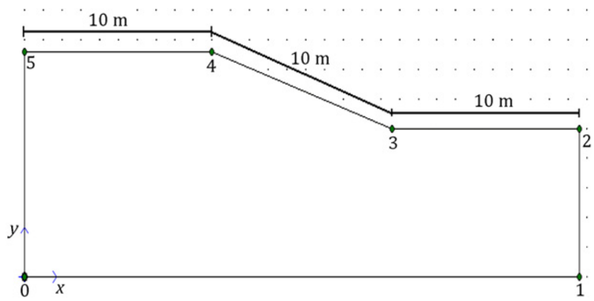

Figure 9: Model slope, type 1, $\alpha = 15°$ [67].

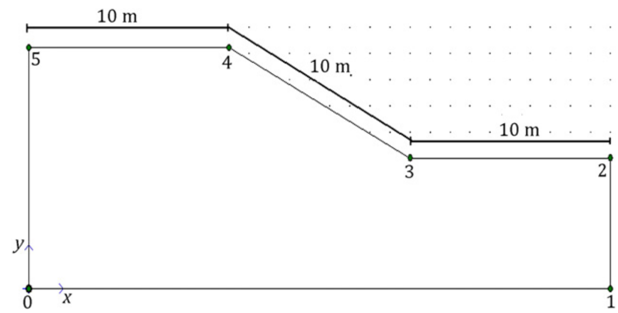

Figure 10: Model slope, type 2, $\alpha = 25°$ [67].

any), etc. In addition to the collected data, lots of observations were made about the failure mechanisms occurring during the experiments, such as translational sliding, collapsing, overturning, displacements, deformations, etc. Table 3 gives the total weight of soils tested in the main experiments, including the density of soil and the date of experiments. Weights of soil were directly related to the degree of compaction. Such weights ranged between 5.05–5.62 kN (or 505–562 kg).

Depths of rainfall infiltration and erosion may vary depending on many parameters including the slope angle used. It was observed in the experiments that as the slope angle increases, the depth of surface erosion increases, due to faster flowing surface runoff. In addition to this, there is the effect of gravity force which is more effective in encouraging vertical infiltration for milder (i.e. near horizontal) slopes, provided that surface cover is non-existent. Another important point is the compaction effort. The denser the soil is, the more the surface erosion, permeability and infiltration tend to decrease for CL-ML type unsaturated soils. Also, rainfall intensity and rainfall duration are other important factors affecting slope stability. But in this study, they were kept constant (as 0.18 $\mathrm{l/s/m^2}$ and 1500 s) for simplicity.

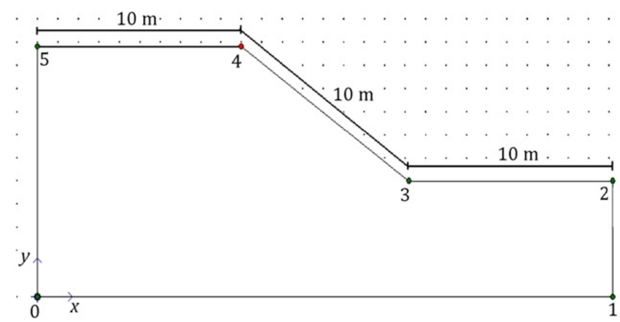

Figure 11: Model slope, type 3, $\alpha = 35°$ [67].

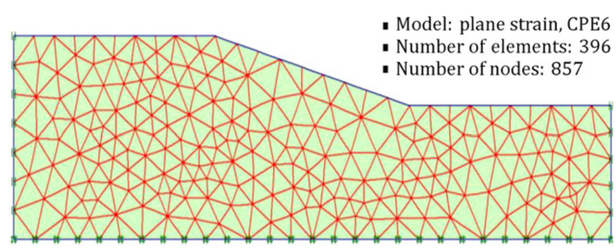

Figure 12: Fine mesh generated model slope, type 1, $\alpha = 15°$ [67].

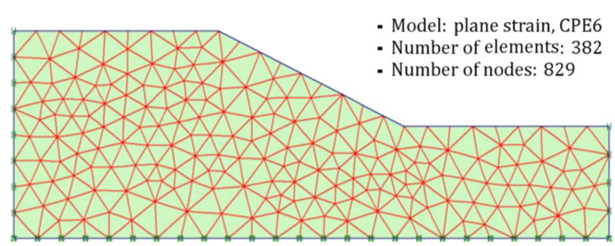

Figure 13: Fine mesh generated model slope, type 2, $\alpha = 25°$ [67].

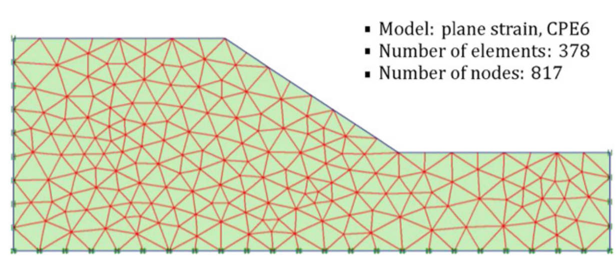

Figure 14: Fine mesh generated model slope, type 3, $\alpha = 35°$ [67].

4. Analysis of the SWIMS tests

In this study, soil used was modeled as a homogeneous, two-dimensional, plane-strain medium. In describing the material properties of the soil used, a Mohr–Coulomb (M–C) plasticity soil model was used. The soil model included six parameters:

- ϕ' Friction angle (°);
- c' Cohesion;
- ψ Dilation angle (°);
- ν Poisson's ratio;
- E Young's modulus ($\mathrm{kN\ m^2}$);
- γ Unit weight ($\mathrm{kN/m^3}$).

A plain strain model of 6 noded triangular elements was selected to be used to generate the finite element mesh. The selected M–C model is based on the elastic-perfectly plastic theory of soil mechanics. Accordingly, both elastic parameters (E, ν) and plastic parameters (c', ϕ', ψ) are utilized in the model. It is noted that similar slope models, constructed and tested under laboratory conditions, should be analyzed. Three different slope angles (α) are used for the analyses: 15, 25, and 35°. Scale factor ratio between the laboratory model and the analysis model is assumed to be: 1/10. Slope heights varied, depending on the slope angle. Slope dimensions used in the FEM (by Plaxis V9 2D) analyses are shown in Figures 9–14.

After the slope geometry was created, parametric soil values obtained from the laboratory tests were entered into the FEM. In addition to the completed laboratory tests, some

Table 3: Summary of the properties of the soil sample used for the SWIMS tests [67].

Test no	Angle of slope (°)	Number of blows	Initial W_c (%)	Weight of soil (kN)	Volume of soil (m^3)	Density of soil, $\gamma_{d(wci)}$ (kN/m^3)	Soil type
1	15	10	14	5.11	0.375	13.60	CL-ML
2	15	10	30	5.05	0.375	13.40	CL-ML
3[a]	15	25	14	5.45	0.375	14.50	CL-ML
4	15	25	30	5.32	0.375	14.20	CL-ML
5	25	10	14	5.15	0.375	13.70	CL-ML
6[b]	25	10	30	5.62	0.375	15.00	90%(CL-ML) + 10%(SP)
7	25	25	14	5.27	0.375	14.10	CL-ML
8[b]	15	10	30	5.52	0.375	14.70	90%(CL-ML) + 10%(SP)
9	35	10	14	5.22	0.375	13.90	CL-ML
10	35	10	30	5.18	0.375	13.80	CL-ML
11	35	25	14	5.41	0.375	14.40	CL-ML
12	35	25	30	5.17	0.375	13.80	CL-ML

[a] Matric suction measurements with tensiometers.
[b] Soil sample consist of 90% CL-ML and 10% SP.

Table 4: Summary of soil parameters used in the FEM [67].

Parameter	Symbol	Value	Unit
Friction angle (eff.)	ϕ'	32	(°)
Cohesion (eff.)	C'	9	(kPa)
Poisson's ratio	ν	0.30	(–)
Young modulus	E	10,000	(kPa)
Dilatancy angle	ψ	0	(°)

Table 5: Summary of the model slope analyses' results with respect to the slope angles [67].

Model type	Factor of safety
15° model slope, GWT[a] is at the GS[b] of the slope	2.902
25° model slope, GWT[a] is at the GS[b] of the slope	1.610
35° model slope, GWT[a] Non-existing in the slope	1.970

[a] GWT: Ground water table.
[b] GS: ground surface.

assumptions were made, such as Young Modulus (E) which was approximated as 10,000 kPa, and Poisson Ratio (ν) which was assumed as: 0.30. Other necessary parameters, such as the angle of internal (effective) friction and (effective) cohesion were taken as the average of the results obtained from the performed direct shear and CU-triaxial tests [75, 79]. Table 4 summarizes the soil parameters used in the FEM analyses.

Table 5 gives the FOS results obtained from the Plaxis analyses performed [67].

Results of the SWIMS tests and slope stability analyses are combined in Table 6 to show soil types, initial water content, proctor's maximum dry density results, factors of safety obtained from the FEM analyses and the degrees of relative compaction obtained [67]. Results are as follows:

1. If the degree of relative compaction increases, the Factor Of Safety (FOS) for the slope stability increases. For small slope angles like $\alpha = 15°$, such an increase is smaller (i.e. slope of the average line is flatter than $\tan\alpha = 0.8$), compared to higher slope angles like $\alpha = 25°$; such an increase is bigger (i.e. slope of the average line is steeper than $\tan\alpha = 1.05$). Figures 15 and 16 present the change of FOS with degree of relative compaction, respectively, for $\alpha = 15°$ and 25° slope angles. It is noted that all 35° slope models have failed by translational failure at the top end of the slope. Movement amounts varying between 3–5 cm. were observed and their Plaxis V9 (FEM) results also gave FOS < 1, which were not plotted.

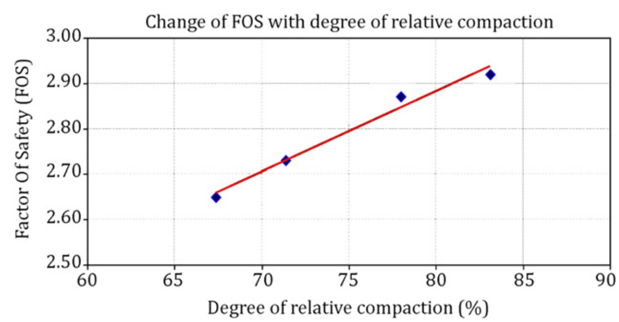

Figure 15: Variation of FOS with degree of relative compaction, $\alpha = 15°$ [67].

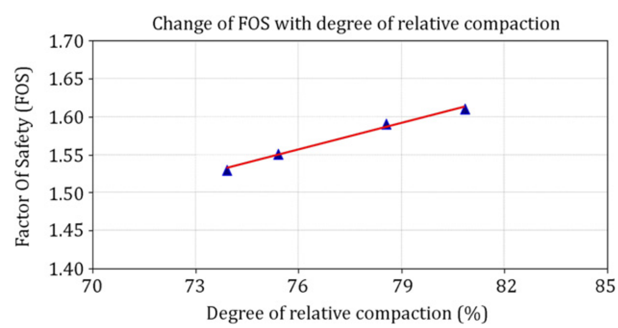

Figure 16: Variation of FOS with degree of relative compaction, $\alpha = 25°$ [67].

2. FOS decreases, if slope angle increases (Figure 17).

Results of the tested SWIMS samples with their initial and final conditions and a comparison of average observed wetting band depths (h_{obser}) vs. the results obtained from the Lump Equation (h_{LE}) are summarized in Table 7.

5. Evaluation of the test results and conclusions

Slope failures in shallow landslides of uncohesive soils are mostly triggered by high intensity and relatively short duration rainfall lasting up to few hours. Rainwater infiltrates into soil and destroys intergranular friction, and effective stress changes due to stress state changes occurring in soil during and after rainfall. In order to study this effect, a specially designed and constructed test apparatus called a "Soil–Water Interaction Modelling System" (SWIMS) was used, with 2 kinds of uncohesive soil (to eliminate osmotic suction effects, associated more strongly with the presence of clay

Table 6: Overall summary of the SWIMS test-results [67].

Test no	Soil type	Wc_i (%)	$\gamma_{\text{dry max}}$ (kN/m^3)	$\gamma_{\text{Model(wcf)}}$ (kN/m^3)	(%) Degree of final compaction	FOS	α (°)
1	CL-ML	0.14	15.30	11.93	77.97	2.87	15
2	CL-ML	0.30	15.30	10.31	67.37	2.65	
3[a]	CL-ML	0.14	15.30	12.72	83.13	2.92	
4	CL-ML	0.30	15.30	10.92	71.39	2.73	
5	CL-ML	0.14	15.30	12.02	78.55	1.59	25
6	CL-ML (%90), SP (%10)	0.30	15.30	11.54	75.41	1.55	
7	CL-ML	0.14	15.30	12.37	80.84	1.61	
8	CL-ML (%90), SP (%10)	0.30	15.30	11.31	73.91	1.53	
9	CL-ML	0.14	15.30	12.19	79.69	<1[b]	35
10	CL-ML	0.30	15.30	10.62	69.38	<1[b]	
11	CL-ML	0.14	15.30	12.63	82.56	<1[b]	
12	CL-ML	0.30	15.30	10.62	69.38	<1[b]	

[a] Matric suction measurements with tensiometers.
[b] Translational failures of 3–5 cm were observed.

Table 7: Summary of the SWIMS tests with initial, final conditions and comparison of average observed wetting band depths (h_{obser}) vs. the results obtained from the Lump's Equation (h_{LE}) [67].

Test no	Wc_f (%)	$\gamma_{\text{dry max}}$ (g/cm^3)	e_f	S_f (%)	k_f(cm/s)	n_f	Wc_i (%)	S_i (%)	h_{LE}(cm)	h_{obser}(cm)
1	0.35	1.35	0.93	0.98	0.000045	0.48	0.14	0.46	0.27	25
2	0.38	1.31	0.99	1.00	0.000055	0.50	0.14	0.46	0.31	25
3	0.34	1.36	0.92	0.97	0.000044	0.48	0.14	0.46	0.27	19.4
4	0.33	1.38	0.89	0.97	0.000041	0.47	0.14	0.46	0.26	18.8
5	0.37	1.31	0.99	0.97	0.000055	0.50	0.14	0.46	0.32	25
6	0.34	1.36	0.92	0.97	0.000044	0.48	0.14	0.46	0.27	18.4
7	0.38	1.31	0.99	1.00	0.000055	0.50	0.30	0.95	3.35	25
8	0.37	1.31	0.99	0.97	0.000055	0.50	0.30	0.95	7.16	25
9	0.38	1.31	0.99	1.00	0.000055	0.50	0.30	0.95	3.35	25
10	0.39	1.29	1.00	0.99	0.000057	0.51	0.30	0.95	3.78	25
11	0.38	1.31	0.99	1.00	0.000055	0.50	0.30	0.95	3.35	17.6
12	0.37	1.31	0.99	0.97	0.000055	0.50	0.30	0.95	7.16	17.7

For the Lumb's equation calculations, k_f, n_f, specific gravity, $G_s = 2.61$, and rainfall duration, $t = 1500$ s, were used.

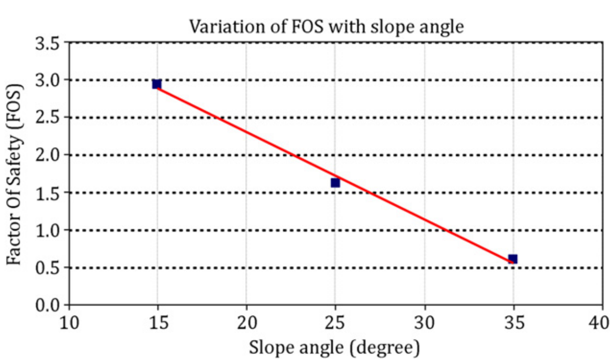

Figure 17: Variation of FOS with slope angle [67].

minerals). These soils had different initial water contents that were compacted under various degrees of compaction, so that the final degrees of saturation are all above 95%, before testing at various slope angles under constant high intensity (0.18 l/s/m^2) and duration (1500 s or 25 min) of rainfall. The reason for ensuring high final degrees of saturation at and above 95% was to allow pore fluid to be in a 3-phase condition i.e. all pore air to be in 'occluded' bubbles moving by a diffusion process in continuous pore water (which may also include some dissolved air) between the soil grains [7,8]. That is why only a limited number of (total) suction measurements (i.e. only in 1 SWIMS test) were attempted to be (directly) measured at 5 locations/depths to obtain one average value at any time, t (s), after rainfall starts, using soil-tensiometers for these tests.

It was then thought that within the wetting band of natural slopes, degrees of saturation were high and the soil shear strength behavior follows the 'saturated' soil mechanics theory more closely, rather than the 'unsaturated' soil mechanics theory, as the latter gets complicated by menisci presence causing suction effects in unsaturated uncohesive soils, which in turn affects soil shear strength behavior. Obtained results in this study are summarized as below:

1. All 35° slopes were failed by translational failure, where the observed movements varied between 3–5 cm when FOS $<$ 1. For the other (15°, 25°) slopes, no failures were observed when FOS $>$ 1 (Table 6).
2. For all slopes used, FOS increased with increasing relative degrees of compaction (in%), and decreased with increasing slope angle (in °) (Figures 15–17).
3. Other parameters, such as soil density, porosity, degrees of saturation, water contents and permeability (water, air) may also affect shear strength/slope stability, especially for low degrees of saturation, where menisci presence and suction effects further govern shear strength behavior, compared to high degrees of saturation ($S > 95\%$), where menisci and suction effects are reduced or minimized to influence soil shear strength behavior.
4. Though the overall correlation between the SWIMS tests' observed wetting band depths (h_{obser}) and the wetting band depths calculated by the Lump Equation (h_{LE}) was poor, the h_{obser} values were much higher than the h_{LE} values. If the initial degrees of saturation (S_i), obtained after sample

compaction at the SWIMS test set-up before applying rainfall, were much lower than 95% (i.e. soil densities would be on the dry side of the optimum water content), correlations were even poorer (Table 7). Alternatively, correlation was slightly better (less poor) for those samples whose S_i $>, =$ 95% before applying rainfall, but the difference gap still remained. The fact of the matter was that Lump's equation [33] grossly underestimated wetting band depths in all tests performed. If the Lump equation in its present form is still considered to be valid, such a conclusion would imply that either water-permeability gradually increases, porosity gradually decreases or both happen towards full saturation; a process which is most likely to happen during a high intensity, short duration rainfall event.

Other recommendations for any future study on uncohesive unsaturated soils could also include studying effects of low intensity (<0.05 l/s/m^2) but prolonged duration (>5 h) rainfall on slope stability/shear strength behavior with monitored (matric) suction using soil-tensiometers, while obtaining the soil–water retention curves (SWRC) of the tested samples, apart from performing direct shear and CD triaxial tests on the thin-walled sampler tube (i.e. Shelby) for obtained (or reconstituted) unsaturated samples. Since total suction is the sum of matric and osmotic suctions, and if cohesive soils are used for the tests, then both suction components should be separately measured, so that their individual effects on the unsaturated soil (slope stability/shear strength) behavior could be better studied.

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