Stabilization of Seepage Induced Soil Mass Movements using Sand Drains

R. Ramkrishnan[1], V. Karthik[2], Mukund S. Unnithan[2], R. Kiran Balaji[2], M. Athul Vinu[2], Anju Venugopalan[2]
[1]*Assistant Professor, Department of Civil Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, Amrita University, India*
[2]*UG Student, Department of Civil Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, Amrita University, India*
E-mail: r_ramkrishnan@cb.amrita.edu

ABSTRACT: Rising groundwater levels increases the pore water pressure in the soil slopes, acting as a triggering factor for landslides. By installing sand drains (horizontal or vertical) along the slope, the groundwater level can be lowered below the critical level, reducing the pore water pressure and also the probability of slope failure significantly. In this study, laboratory-scale soil slopes of varying geometry were modelled in a tank and constant inflow was provided to simulate groundwater flow. With and without loading, the critical phreatic levels for the various slopes were determined. Vertical sand drains were then installed along the slope and the tests were repeated for a fixed duration. It was found that the slopes did not fail and remained stable for a longer time period, even with increase of groundwater flow. Hence it was concluded that sand drains are a feasible slope stabilization technique even on slopes subjected to static loading.

KEYWORDS: Sand slopes, Groundwater fluctuation, Sand drains, Slope failure, Slope stabilisation

1. INTRODUCTION

Landslides occur due to various reasons which include seismic disturbance, human activities (mining, overgrazing, and deforestation) and hydrological actions (floods, rainfall and groundwater fluctuation). A few of the most destructive landslides caused as a result of hydrological action are Vajont landslide (Italy, 1963), Vargas tragedy (Venezuela, 1999), Southern Leyte mudslide (Philippines, 2006), Kedarnath floods (India, 2013), etc. Hence, in this study an effort is made to analyse the relation between the fluctuating water levels and the stability of slopes and effectively use sand drains to stabilize the same. The rise of water level can be due to direct rainfall at the location or due to heavy rains in a nearby place. The former one can also result in the ground being washed away, leading to surficial failure (Tohari et al.2007), while the latter is being discussed here.

In this study, slope stability analysis was conducted on a laboratory scale soil-slope model, where sand slopes were constructed in a metallic tank (2.3m x 1.2m x 1m) by air pluviation. Groundwater flow was induced in the slope with the help of an adjacent chamber. Slopes of varying geometries were constructed in the tank and were subjected to a continuous rise of groundwater. The maximum groundwater level at which the slope failed was determined for various slope geometries. It was observed that, failure could be averted if the toe was prevented from getting completely saturated. This could be made possible by providing a drainage medium to remove the water, thus not allowing the phreatic level to progress above the toe(Rahardjo et al. 2011). Sand drains are generally bore holes which are filled with coarse sand (having more voids), which aid in ground dewatering and compaction. Due to higher voids, the coarse sand acts as a sink, and water from the surrounding area gets collected in these drains, which can then be pumped out. Hence, sand drains can be used for this function, as it provides an easier path for the water to permeate through (Choi 1983). Sand drains have been vastly used for the consolidation of embankments, as they increase the rate of drainage in the embankment (Indraratna et al. 2008). Sand drains can be prefabricated and driven into loose sands, bored and cast in-situ or prefabricated and bored into dense sand or clayey soils.In this study, vertical sand drains were considered for slope stabilization and were introduced in the slope. This was done to check if the vertical sand drainsaided in stabilizing the slope as discussed above.

2. LITERATURE REVIEW

Slope stability has always been one of the trending research topics and considerable research work has been conducted in the past. The studies were directed in order to find various failure causing parameters and also their direct or indirect effects on slope stability. Monitoring various parameters such as deformation (Sasahara 2001), pore-water pressure (Yagi and Yatabe 1987), soil suction (Kitamura et al. 1999), groundwater depth (Yokota et al., 2000) and acoustic emissions (Kousteni et al. 1999), at critical locations within a slope have been carried out previously. It was found that hydrological factors were the driving forces in most of the failures. Laboratory tests were carried out to further study the effect of rainfall and groundwater variations on slopes(Orense et al. 2004, Huat et al. 2006, Ahmad 2008, Egeli and Pulat 2011, Vandamme and Zou 2013).

After extensive research, it was found that failure occurs when the toe of the slope getssaturated and the moisture content of the soil present there reachesa threshold value almost equal to its liquid limit. It was also practically found that water infiltration through soil (rainfall) caused minor surficial movement of soil and led to the formation of small cracks upslope. Major deep seated failure of the slope occurred only when the groundwater level started to increase gradually, as it increased the pore water pressure and saturation ratio of the slope (Orense et al. 2004, Ahmad 2008).Tests were conducted in the past to induce rainfall in laboratory scale models and failure initiation was studied upon. It was found that a localized instability near the toe can subsequently disturb the upper portion of the slope, and lead to failure of even the unsaturated soil on the slope surface (Tohari et al. 2007). Once the causes of failure were analysed, the next step was to find solutions to mitigate such failures. Hence it was inferred that, in order to prevent the slope from failing, some technique must be applied to prevent the toe portion from getting completely saturated (Ahmad 2008). Drainage methods like horizontal drains (Lau and Kenny 1984, Martin and Siu 1996,Santi et al. 2001, Rahardjo et al. 2003, 2011, Mukhlisin and Aziz 2016), prefabricated vertical drains(Bergado et al. 2002, Chu et al. 2004, Ghandeharioon et al. 2012, Vytiniotis and Whittle 2013), vertical sand drains (Casagrande and Poulos 1969), etc. thus gained popularity, and were studied in detail as a method for stabilizing slopes. Horizontal drains were also found to be effective and it wasfound that placing horizontal drains near the toe of the slope was more effective in lowering the groundwater level. The spacing of the drains also affected the efficiency of the drains -if the spacing was too large, then the effectiveness of the drains was reduced (Choi 1983). Apart from the experimental data, analytical studies using finite element methods were carried out to predict the occurrence of slope failures (Choi 1983, Rabie 2014). From these observations, it was evident that there were very limited studies on loaded slopes; i.e., how the application of a static load would affect the slopes' stability. Also, there were limited data on vertical sand drains being used as a drainage medium. Hence, this study is an attempt to address the existing knowledge gap.

3. MATERIALS AND METHODOLOGY

3.1 Material Properties

Modelling of slopes and sand drains were done using sand; which was sieved to obtain the required size. For creating the slope, fine sand passing through 1mm IS sieve was taken and for the sand drains; coarse sand passing through 4.75mm IS sieve and retained on 2.36mm IS sieve was used. After sieving, both coarse and fine sand were tested for their basic engineering properties like permeability, shear parameters, particle size, void ratio, etc. (IS 2720)and the determined properties are tabulated in Table 1.

Table 1 Parameters of Sand

Parameter	**Fine Sand**	**Coarse Sand**
Dry unit weight (kN/m^3)	17.0	14.9
Natural void ratio (e)	0.519	0.569
Minimum void ratio (e_{min})	0.462	0.580
Maximum void ratio (e_{max})	0.738	0.731
Relative Density (I_D) (%)	79.4	47.7
Specific Gravity	2.64	2.52
Permeability (m/s)	4.44e^{-5}	8.95e^{-5}
Angle of internal friction (ϕ)	36.3^0	34.6^0

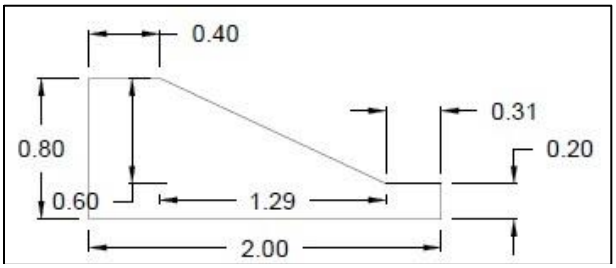
3.2 Laboratory Testing

A tank with dimensions 2.30m x 1.00m x 1.20m was fabricated, as shown in Figure 1. A perforated metal sheet was provided to separate the tank into two chambers. Woven geotextile (base material – Polyamide, opening size –US sieve 70 (0.212mm)) was used to wrap the perforated metal sheet, allowing water to flow, but preventing soil intrusion. Slopes were created in the tank by using a pluviation setup, which consisted of a pulley system and a pluviation device with the same concept as Tatsuoka et al. (1982) and Vaid and Negussey (1984). Upon calibration it was found that the sand achieved uniform and maximum relative density when pluviated through air, from a height of 20cm (maximum relative density of 59.67%). Slopes were created with a crest height of 0.8m and a toe height of 0.2m. The slope dimensions are given in Table 2 and a schematic layout of the slopes and instrumentation is represented in Figure 2 and Figure 3 (a), (b) and (c) respectively.

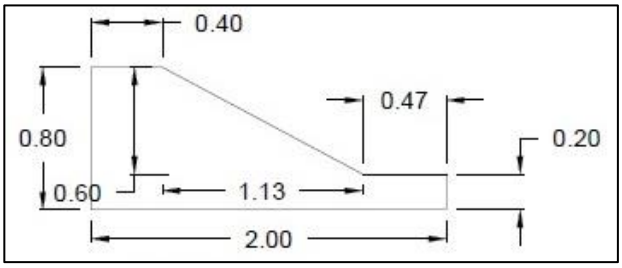
Figure 1 Tank and Manometer Setup

Table 2 Slope Dimensions

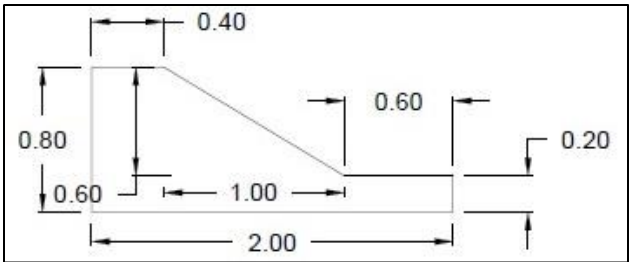
Slope Angle	**Length (cm)**		
	Crest	Slope	Toe
25°	40	129	31
28°	40	113	47
31°	40	100	60



(a) 25°slope



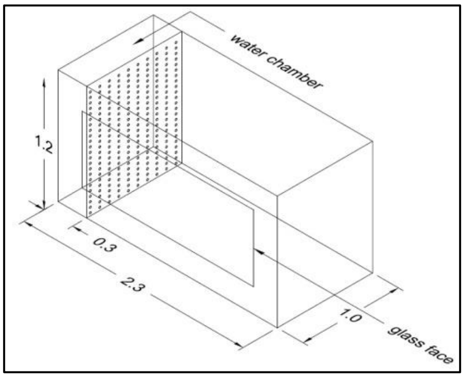
(b) 28°slope



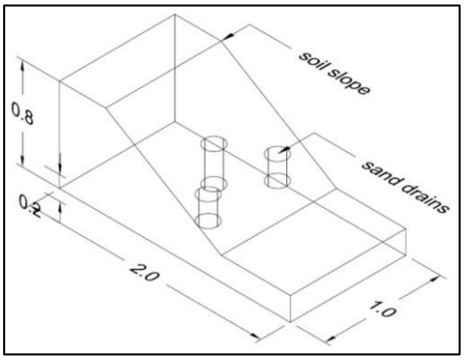
(c) 31° slope

Figure 2 Schematic layouts of the various slope angles

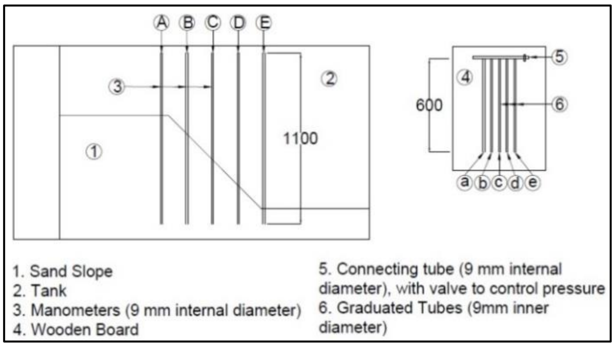
A set of pilot tests were conducted to determine the slope angles and it was found that the maximum slope angle that could be constructedby pluviation was 31^0. Various slope angles of 25°, 28° and 31° were considered as one parameter for the study. A manometric setup was designed and modelled to monitor the variations in the induced phreatic level of the soil slope (Conte and Tronconne 2011). Five manometer tubes, 1.1m long and 9mm internal diameter were placed at equal intervals along the length of the slope and were connected to another set of five glass tubes, of length 0.6m and 9mm inner diameter placed on a wooden board, as shown in Figure 1. The manometric setup was calibrated by inserting the tubes in a small tank filled with the same sand. Water was poured into the tank, and the height of water inside the tank and the manometer were measured periodically. Upon calibration, it was found that 1cm rise of water in the manometer corresponds to 3cm rise of water in soil. With the aid of these calibrated manometric readings, the variation of the phreatic level in the sand slope was continuously monitored and recorded.



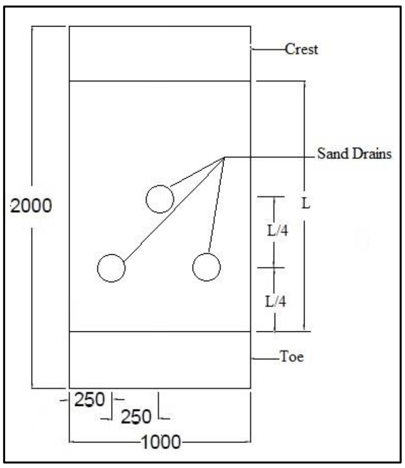
(a) Tank model



(b) Slope model with sand drains



(c) Manometric Setup



(d) Sand Drain Installation – Plan

Figure 3 Schematic Layout of Instrumentation

The test consisted of four different cases:

- Case 1 - Homogeneous sand slope with groundwater flow
- Case 2 - Homogeneous sand slope with groundwater flow and static loading
- Case 3 - Homogeneous sand slope with groundwater flow (with sand drains)
- Case 4 - Homogeneous sand slope with groundwater flow and static loading (with sand drains)

In order to study and compare the slope stability when the slope is subjected to a certain intensity of static loading, a metal plate of dimensions 0.85m x 0.35m x 0.1m was placed on the crest of the slope. The metal plate was chosen for two reasons: (i) to resemble an average footing where length is less than or equal to 2.5 times the breadth ($l \leq 2.5b$), (ii) to ensure there is no bending of the plate andthat the plate settles uniformly when loaded. Dial gauges were fixed on both sides of the plate to measure the settlement. Concrete blocks of dimensions 390mm x 190mm x 140mm and weighing 18kg were incrementally placed on the metal plate as shown in Figure 4, with a time gap of 5 seconds between each load increment. The number of blocks placed was fixed (weighing 144kg) to ensure that the slope crest experienced only immediate settlement (less than 2mm), which is similar to the settlement ground surfaces undergo during usual construction processes.

Three vertical sand drains of 9cm diameter were used for testing and the spacing was taken as a quarterof the slope length (Cook et al. 2008). The number and spacing of the drains were decided based on the results of the pilot tests and previous studies. On trying various combinations, maximum efficiency was observed when two drains were placed near the toe of the slope and one drain placed in the slope, as shown in Figures 3(d) and 5. These drains were connected to a pump and water was pumped out when failure was incipient. The critical phreatic level for slopes without static loading was obtained beforehand and the sand drains were operated when the phreatic level in the slope was close to the same.The tests involving sand drains wereperformed for a total of 250 minutes, such that the sand drains could be operated for at least 60 minutes more than the time it took for the previous slope to fail; proving the efficiency of the proposed method.

Figure 4 Loading setup

Figure 5 Slope incorporated with sand drains and dial gauges

3.3 Experimental Procedure:

Pilot tests were conducted to determine the slope geometry and to calibrate the manometric setup; after which, the slope was constructed. The experiment was carried out in four steps:

- Slopes of varying angles were constructed and ground water was introduced. The critical phreatic level at which the slope failed was determined.
- Slopes of varying geometry were constructed, and fixed load intensity was applied. Ground water was introduced and the critical phreatic level at which the slope failed was determined.
- The same slopes were then constructed with the inclusion of sand drains without any static loading. The number of sand drains was kept constant and the spacing between the drains was changed according to the slope. Groundwater was then induced. Water from the sand drains was pumped out when the water level almost reached the respective critical phreatic levels for the particular slope geometry. The test was continued until the rate of outflow exceeded the rate of inflow for a considerable duration.
- The same slopes were then constructed along with sand drains, and the predetermined static load was introduced.Groundwaterwas then induced. Water from the sand drains was pumped out when the water level almost reached the critical phreatic level. The test was continued until the rate of outflow exceeded the rate of inflow for a considerable duration.

For the tests that involved static loading, a load-settlement curve was obtained by observing the settlement using dial gauges (Anil Kumar and Ilamparuthi 2009). The settlement values were recorded at fixed time intervals.

3.4 Analytical Testing

The verification of test models was done using PLAXIS 2D (Anil Kumar and Ilamparuthi 2009), where homogeneous slopes of varying geometry were modelled. The critical phreatic level obtained from the experiment for Case 1 (Homogeneous sand slope with groundwater flow) and Case 2 (Homogeneous sand slope with groundwater flow and static loading)was incorporated in the analytical study. The slopes were checked for failure and their failure patterns were observed and compared with the experimental results.

The boundary conditions taken for the analysis was 20 cm,such that it resembled the experimental setup. Standard fixities were established and the mesh size was set to global very fine as shown in Figure 6. Mohr-Coulomb material model was used to analyse the drained material type. Table 3 lists the various soil properties used for the analysis. Pore pressure distribution was inputted as general phreatic level after modelling the critical phreatic level.

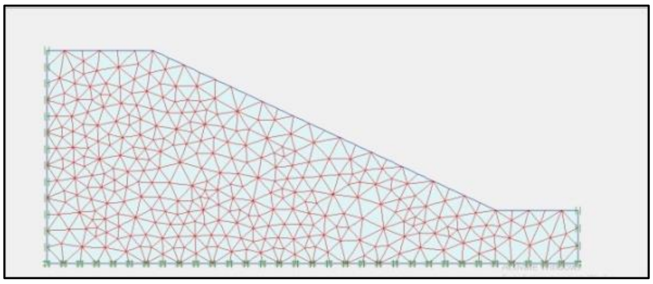


Figure 6 Standard fixities and Mesh

Table 3 Soil parameters for Analytical Study

Parameter	Fine Sand
Dry unit weight (kN/m^3)	15.2
Saturated unit weight (kN/m^3)	19.2
Void ratio	0.703
Specific Gravity	2.64
Permeability (m/s)	4.44e^{-5}
Stiffness (kN/m^2)	10
Angle of internal friction (ϕ)	36.3°

4. RESULTS AND DISCUSSIONS

4.1 Experimental Results

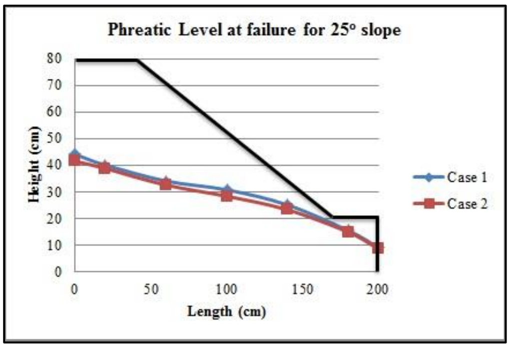
For all the four cases that were experimented, the rate of outflow from the bottom drains of the tank was measured at frequent intervals and was found to be 1.2 m^2/min for all slope angles, after toe saturation had occurred.

The first two cases of experimentation were on homogeneous sand slopes (25°, 28°and 31°) without and with static loading. For the various slope geometries, the phreatic level readings in the corresponding manometers and the time at which slope failure had occurred, for both the cases are shown in Table 4.

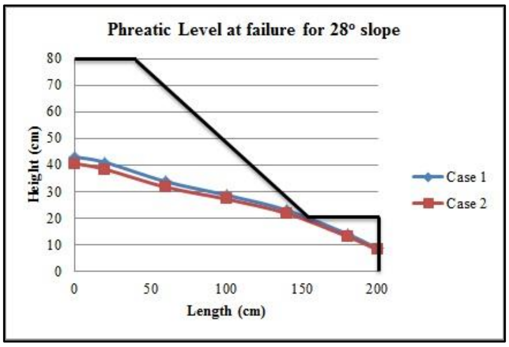
Table 4 Phreatic Levels at Failure [Case 1 and Case 2]

Slope Angle	Time at failure (min)	Phreatic Level (cm)					
		Water Chamber	Manometer Tube 1	Manometer Tube 2	Manometer Tube 3	Manometer Tube 4	Manometer Tube 5
Without Static Loading [Case 1]							
25^0	182	44	40	34	30.7	25	15.4
28^0	163	43	40.9	33.7	28.6	22.9	13.9
31^0	160	41	39.1	31.9	25.3	19.6	13.6
With Static Loading [Case 2]							
25^0	140	41.5	38.7	32.5	28.3	23.2	14.8
28^0	138	40.5	38.3	31.6	27.1	21.7	13
31^0	136	39	35.9	30.4	24.4	18.1	13

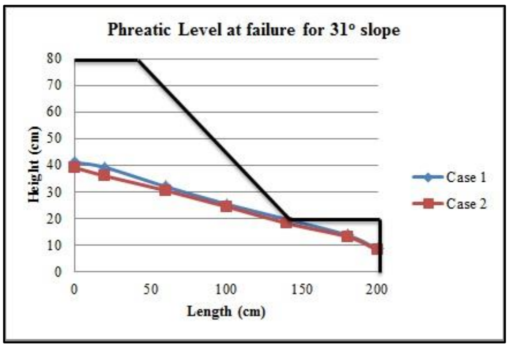
Figure 7 (a), (b),and (c) represent the phreatic level at failure for three slope geometries, giving a comparison between the phreatic level at failure for both cases (with and without static loading).



(a) 25^0 slope



(b) 28^0 slope



(c) 31^0 slope

Figure 7 Phreatic Levels at Failure

From the obtained readings and graphs, it can be observed that when static loading was applied to the slope, the time taken for slope failure to occur was lesser than for the case with no static loading. Also, the phreatic level at failure for Case 2 is comparatively lower than that from Case 1.When static loading was applied, the sand particles directly under the loaded area underwent compaction, rearranging the particles, resulting in a denser packing, which in turn reduced the permeability of that region. Hence, it was observed that the rise of groundwater inside the slope reduced. But, the water level in the water chamber increased, thereby increasing the head causing flow. This increase in head caused the water to flow faster in the horizontal direction inside the slope, thereby causing the slope to fail early. A typical slope failure pattern observed during the experimental analysis is shown in Figure 8.

Figure 8 Slope Failure Pattern

For Case 2, from the settlement data recorded; a pressure settlement curve, as shown in Figure 9, was plotted by taking the average settlement values from the two dial gaugesat crest.

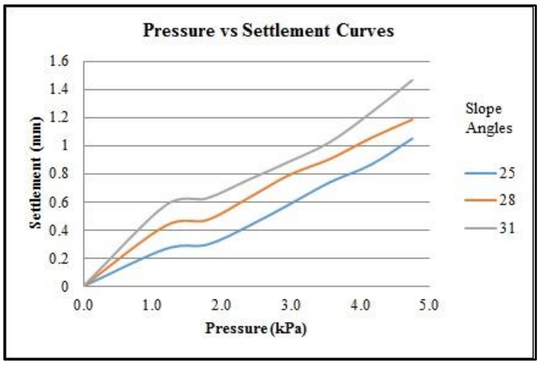


Figure 9 Pressure vs. Settlement Graphs for Static Loading [Case 2]

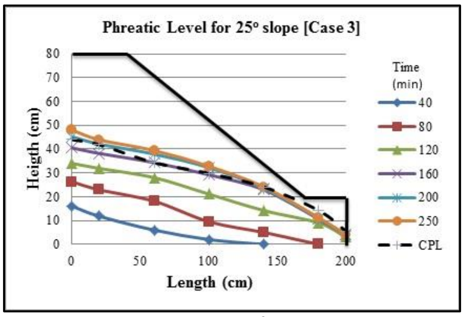
From the pressure settlement graph, it can be suggested that, on application of sudden static loads, the sand particles under the loading plate underwent immediate settlement, shown by the sudden rise in the settlement value. On successive increments, the settlement became more gradual. This can be correlated to the settlement that might occur during the construction phase in any site condition. During construction, the loading on the soil stratum is incremental and after construction it becomes a static fixed load.

The gradual increase in the settlement values in the time settlement graphs, during ground water flow can be attributed to the lubrication of sand particles when water seeped into the soil mass; which enabled the particles to easily slide over each other. Hence, the sand particles got arranged in a more compact manner. By performing similar loading tests on soils taken from the site and by considering the meteorological data for that site, it will be possible to predict a certain maximum load that can be carried by the slope without undergoing failure.

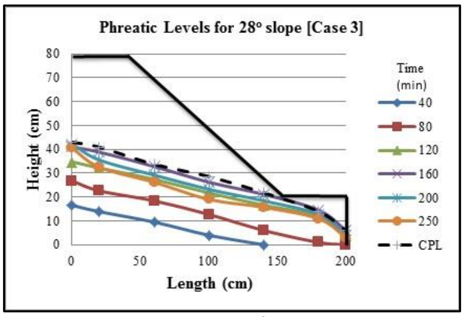
The last two cases of experimentation involved the incorporation of sand drains into the various slope geometries, with and without loading. In these two cases, the sand drains were operated when the phreatic level in the slope almost reached the critical phreatic level [CPL], obtained from the first two cases. The critical phreatic levels (from Case 1) and the phreatic levels after operating the sand drains of the respective slope geometries are shown below in Table 5 and the respective phreatic levels are shown graphically in Figure10 (a), (b) and (c).

Table 5 Phreatic Levels after Operating Sand Drains [Case 3]

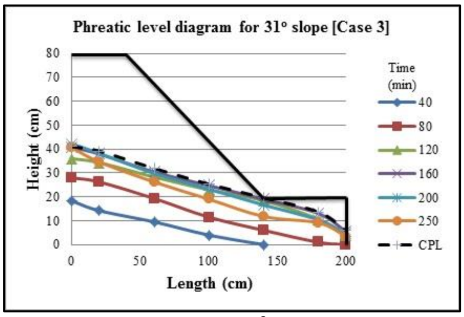
Slope Angle	Time (min)	Phreatic Level (cm)					
		Water Chamber	**Manometer Tube 1**	**Manometer Tube 2**	**Manometer Tube 3**	**Manometer Tube 4**	**Manometer Tube 5**
		Critical Phreatic Level [Case 1]					
25^0	182	44	41.8	34.3	29.8	24.1	14.2
28^0	163	43	40.9	34	28.9	23	13.9
31^0	160	41	39.1	31.9	25.3	19.6	13.6
		Phreatic Level after Operation of Sand Drains [Case 3]					
25^0	250	48	43.9	39.4	32.8	33	11.2
28^0	250	40.5	32.5	26.2	19	15.7	10.9
31^0	250	40.5	34.6	26.2	19	11.8	9.1



(a) 25^0 slope



(b) 28^0 slope



(c) 31^0 slope

Figure 10 Phreatic Levels after Operating Sand Drains

Comparing the above results with the results from Case 1, it can be observed that; by pumping out water using sand drains, the slope was prevented from failure for a prolonged duration. By operating the sand drains, the phreatic level was maintained well below the critical phreatic level.

Considering the 31^0 slope, it was earlier found that the slope had failed at 160 minutes with a continuous inflow rate of 2.5 m^2/min. With the introduction of sand drains, at the same inflow rate, the groundwater could be successfully maintained below the critical phreatic level. It was observed that the slope remained stable even after 250 minutes of similar inflow, as the groundwater wasn't allowed to rise any further. The rate of rise in groundwater level after sand drains were operated was much lower when compared to the rate of rise before operating the sand drains, as shown in Table 6.Also, when the sand drains were operated, the rate of outflow increased and gradually became steady and was greater than the rate of inflow, thereby preventing the slope from failure.

Table 6 Rate of rise in groundwater level for all cases

Case Description	Rate of rise in water table (cm/hr)		
	25^0 slope	28^0 slope	31^0 slope
Case 1	10.3	11.5	10.7
Case 2	11.9	11.8	11.0
Case 3 (before sand drain operation)	10.1	11.8	12.6
Case 3 (after sand drain operation)	0.158	-2.99	-1.65
Case 4 (before sand drain operation)	-	-	10.2
Case 4 (after sand drain operation)	-	-	-0.119

For the last case of testing, the steepest slope geometry (31^0slope) was considered for conducting the experiment. The critical phreatic level (from Case 2) and the phreatic level after operation of sand drains is shown in Table 7 and the corresponding

Table 7 Phreatic Level after Operating Sand Drains [Case 4]

Slope Angle	Time (min)	Phreatic Level (cm)					
		Water Chamber	Manometer Tube 1	Manometer Tube 2	Manometer Tube 3	Manometer Tube 4	Manometer Tube 5
Critical Phreatic Level [Case 2]							
31^0	136	39	35.9	30.4	24.4	18.1	13
Phreatic Level after Operation of Sand Drains [Case 4]							
31^0	250	39.25	32.6	30.7	23.2	17.2	11.8

values are represented graphically in Figure 11.Also, the settlement data obtained from the test were used to obtain the pressure settlement curve, as shown in Figure 12.

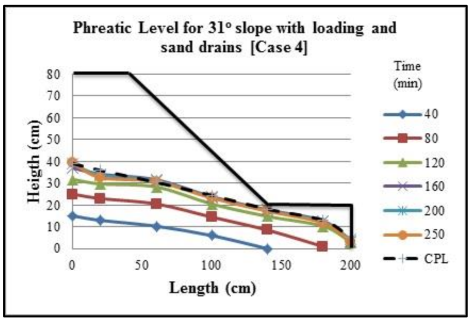


Figure 11 Phreatic Levels after Operating Sand Drains [Case 4]

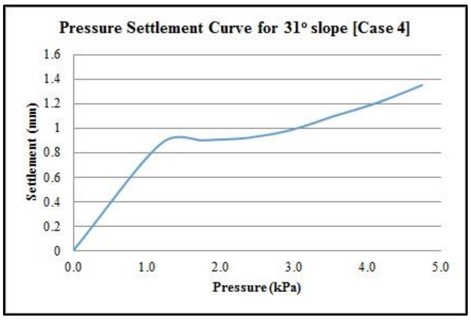


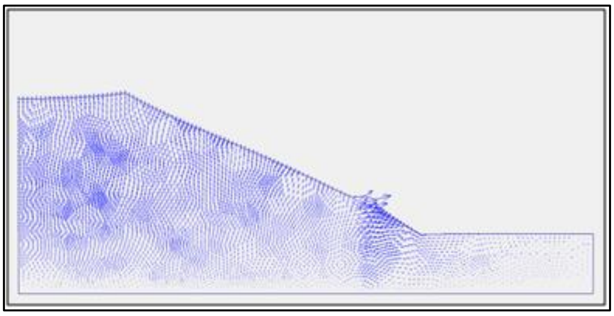
Figure 12 Pressure vs. Settlement Curves for Case 4

It was observed that the settlement was gradually increasing until the sand drains were operated. The rate of settlement at the crest of the slope, caused by the applied static loading was found to reduce after the sand drain operation has started. This suggests that, before the sand drains were operated, due to rise in groundwater level, the sand particles that were submerged got lubricated and slid over each other to get compacted more effectively. When the sand drains were operated, the groundwater level was not allowed to rise any further, preventing the sand above the groundwater from getting submerged. This prevented further lubrication and rearrangement of soil particles to contribute to better compaction. The sand particles were compacted only due to the action of the load.

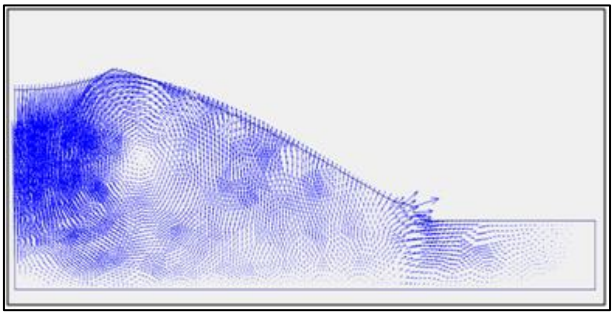
An added advantage of using sand drains for slope stabilization is that it can act as a source of water too. In places subjected to heavy rainfall, groundwater entering the slope can be pumped out through the sand drains at maximum capacity. Along with stabilizing the slope, the pumped out water can be stored and used for various other domestic purposes. In case the groundwater inflow rate exceeds the capacity of the pump, by operating the sand drains, the slope can be temporarily stabilized and the approximate time at which the slope might fail can be predicted. This provides enough time to evacuate people and livestock from the areas under danger, thereby preventing loss of lives.

4.2 Analytical Results

The critical phreatic levels obtained for Case 1 and 2 in the experimental study were used to perform the PLAXIS analysis. The displacement at failure, predicted by the software was similar to the failure observed during the experimental study (failure occurs above the toe of the slope). Hence, the experimental procedure and the manometer readings for the water levels were validated. The total displacement diagrams at failure for the 31^0 slope, for Cases 1 and 2 are shown in Figure 13 (a) and (b) respectively. Figure 14 shows the predicted pore pressure contours for 31^0slopes.



(a) Case 1



(b) Case 2

Figure 13 Displacement diagram at failure for 31^0slope

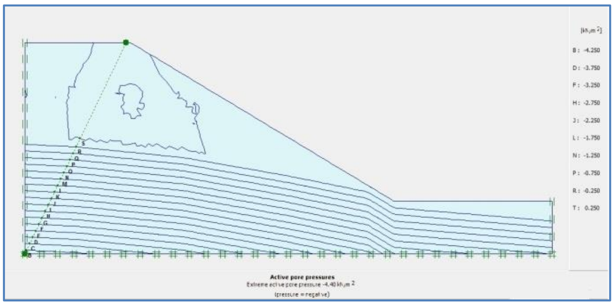


Figure 14 Predicted pore pressure contours for 31^0slope

5. CONCLUSION

From the experimental data and results, it can be observed that, groundwater fluctuation is the underlying reason for slope failure. The failure of the slopes occurred due to the saturation of the slope near the toe region. Also, on steeper slopes, the phreatic level at failure and the time taken for the slope to fail reduced, indicating that they are more unstable. When a slope was subjected to building and other static loads, the soil undergoes compression, and when compared to similar slopes without loads; slope failure occurred faster, at a lower phreatic level.

The usage of sand drains to prevent slope failure was then experimented, and the results obtained indicate that the slopes could be stabilized for a prolonged duration. This was achieved by operating the sand drains to maintain the water level below the critical phreatic level. Even on loaded slopes, sand drains were found to be an effective option for slope stabilization.

Generally, the natural soil slopes will contain a certain amount of clay content. The permeability of the soil decreases with increase in clay content. In such scenarios, usage of sand drains to dewater the slopes will be more efficient as the drains will act as a sink. In this study, fine sand was used to model the slopes due to their uniformity and higher permeability (considering the short duration of the project). If sand drains with permeability slightly higher than the in-situ soil is an efficient stabilization technique; such drains will also be effective on slopes with clay content (lesser permeability).

Future studies can include large scale centrifuge models to study the behaviour of sand slopes to groundwater fluctuation, dynamic loading on the crest, usage of soil excavated from slopes to create models and obtain results with more relevance.

The sand drains can be made site specific when they are used for slope stabilization in field conditions. From the meteorological data and the rainfall pattern for a given area, the rate of groundwater inflow/rise in the slope can be determined. Using this rainfall data, the sand drains can be designed by considering parameters like permeability and particle size distribution of the sand being used, inflow rate, diameter and depth of sand drains, pump capacity, etc.

6. ACKNOWLEDGMENT

We would like to express our gratitude to Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, Amrita University, India for funding the project and for providing the necessary facilities required for the successful completion of the project.

We express our heartfelt thanks to Dr. N. Narayana Pillai, Dr. K. Sreevalsa and Mr. K. Sreenivasan, for their support and guidance. We would also like to thank Mr. D. Ravichandran and Ms. K. Manasa, for their active contribution to the same. Also, we would like to thank all our friends and family for their contributions to our work.

7. REFERENCES

Ahmad, M. (2008) “Effect of Groundwater Level toward Slope Stability”, Bachelor of Engineering (Hons), Universiti Teknologi PETRONAS, Perak, Malaysia.

Anil Kumar, S.V., and Ilamparuthi, K. (2009) “Response of Footing on Sand Slopes”, Indian Geotechnical Conference-2009, 1, pp 622-626.

Bergado, D., Balasubramaniam, A., Fannin, R., and Holtz, R. (2002)"Prefabricated vertical drains (PVDs) in soft Bangkok clay: a case study of the new Bangkok International Airport project”. Canadian Geotechnical Journal, 39(2), 304-315.

Budhu, M., and Gobin, R. (1996) “Slope Instability from Ground-Water Seepage”, Journal of Hydraulic Engineering, 122, Issue 7, pp 415-417.

Casagrande, L. and Poulos, S. (1969) "On the Effectiveness of Sand Drains". *Canadian Geotechnical Journal*, 6(3), 287-326.

Cascini, L., Calvello, M., and Grimaldi, G. (2010) “Groundwater Modelling for the Analysis of Active Slow-Moving Landslides”, Journal of Geotechnical and Geoenvironmental Engineering, 136, Issue 9, pp 1220-1230.

Choi, E. (1983) “Seepage around Horizontal Drains in Hill Slopes”, Journal of Hydraulic Engineering, 109, Issue 10, pp 1363-1368.

Chu, J., Bo, M., and Choa, V. (2004) "Practical considerations for using vertical drains in soil improvement projects”. Geotextiles and Geomembranes, 22(1-2), 101-117.

Conte, E., and Tronconne, A. (2011) “Analytical Method for Predicting the Mobility of Slow-Moving Landslides owing to Groundwater Fluctuations”, Journal of Geotechnical and Geoenvironmental Engineering, 137, Issue 8, pp 777-784.

Cook, D., Santi, P., and Higgins, J. (2008) “2007 AEG Student Professional Paper: Graduate Division: Horizontal Landslide Drain Design: State of the Art and Suggested Improvements”, Environmental and Engineering Geoscience, 14, Issue 4, pp 241-250.

Egeli, I., and Pulat, H. (2011) "Mechanism and modelling of shallow soil slope stability during high intensity and short duration rainfall". Scientia Iranica, 18(6), 1179-1187.

Evans, S.G., Guthrie, R.H., Roberts, N.J., and Bishop, N.F. (2007) “The disastrous 17 February 2006 rockslide-debris avalanche on Leyte Island, Philippines: a catastrophic landslide in tropical mountain terrain” (PDF), Natural Hazards and Earth System Sciences, 7, pp 89–101.

Genevois, R., and Ghirotti M. (2005) “The 1963 Vaiont Landslide” (PDF), Giornale di Geologia Applicata, 1, pp 41–52.

Ghandeharioon, A., Indraratna, B., and Rujikiatkamjorn, C. (2012). "Laboratory and Finite-Element Investigation of Soil Disturbance Associated with the Installation of Mandrel-Driven Prefabricated Vertical Drains". *Journal of* Geotechnical and Geoenvironmental Engineering, 138(3), 295-308.

Huat, B., Ali, F., and Low, T. (2006)."Water infiltration characteristics of unsaturated soil slope and its effect on suction and stability”. Geotechnical and Geological Engineering, 24(5), 1293-1306.

Indraratna, B, Aljorany, A. and Rujikiatkamjorn C. (2008) “Analytical and numerical modeling of consolidation by vertical drain beneath a circular embankment”, International Journal of Geomechanics, 8, Issue 3, pp 199-206.

Kitamura, R., Jomoto, K., Yamamoto, K., Terachi, T., Abe, H., and Iryo, T. (1999). “Field measurement of suction in soil and rainfall in Kagoshima Prefecture”, Proceedings, 1st International Symposium on Slope Stability Engineering, Shikoku, 1, pp 141-145.

Kousteni, A., Hill, R., Dixon, N., and Kavanagh, J. (1999) “Acoustic emission technique for monitoring soil and rock slope instability”, Proceedings, 1st International Symposium on Slope Stability Engineering, Shikoku, 1, pp 151-156

Lau, K. and Kenney, T. (1984). "Horizontal drains to stabilize clay slopes". Canadian Geotechnical Journal, 21(2), 241-249.

Martin, R. P. and Siu, K. L. (1996) Use of Horizontal Drains for Slope Stabilisation in Hong Kong, HKIE Transactions, 3:2, 25-36

Mukhlisin, M. and Aziz, N. (2016)."Study of horizontal drain effect on slope stability”. Journal of the Geological Society of India, 87(4), 483-490.

Orense, P.R., Shimoma, S., Maeda, K., and Towhata, I. (2004) “Instrumented Model Slope Failure due to Water Seepage”, Journal of Natural Disaster Science, 26, Issue 1, pp 15-26.

Pradel, D., and Raad, G. (1993) “Effect of Permeability on Surficial Stability of Homogeneous Slopes”, Journal of Geotechnical Engineering, 119, Issue 2, pp 315-332.

Punmia, B.C., Jain, A.K., and Jain, A.K. (1970). “Soil Mechanics and Foundations”, Laxmi Publications (P) Ltd, New Delhi, India, pp430-432, pp 615-616.

Rabie, M. (2014) “Comparison study between traditional and finite element methods for slopes under heavy rainfall”. HBRC Journal, 10, Issue 2, pp 160-168.

Rahardjo, H., Hritzuk, K., Leong, E., and Rezaur, R. (2003)."Effectiveness of Horizontal Drains for Slope Stability”. Engineering Geology, 69(3-4), 295-308.

Rahardjo, H., V.A. Santoso, E.C. Leong, Y.S. Ng and C.J. Hua (2011). “Performance of Horizontal Drains in Residual Soil Slope”. Soils and Foundations, Japanese Geotechnical Society, June, Vol. 51, No.3, pp. 437-447

Santi, P., Elifrits, C., and Liljegren, J. (2001)."Design and Installation of Horizontal Wick Drains for Landslide Stabilization”. Transportation Research Record: Journal of the Transportation Research Board, 1757, 58-66.

Sasahara, K. (2001) “Mechanical model for prediction of steep sandy slope failure due to rainfall using surface displacement”, Tsuchi-to-Kiso, 49, Issue 7, pp 13-15.

Tatsuoka, F., Muramatsu, M., and Sasaki, T. (1982) “Cyclic undrained stress-strain behavior of dense sand by torsional simple shear tests”, Soils and Foundations, 22, Issue 2, pp 55-70.

Tohari, A., Nishigaki, M., and Komatsu, M. (2007) “Laboratory Rainfall-Induced Slope Failure with Moisture Content Measurement”, Journal of Geotechnical and Geoenvironmental Engineering, 133, Issue 5, pp 575-587.

Vaid, Y., and Negussey, D. (1984) “Relative density of pluviated sand samples”, Soils and Foundations, 24, Issue 2, pp 101-105.

Vandamme, J. and Zou, Q. (2013)."Investigation of slope instability induced by seepage and erosion by a particle method”. Computers and Geotechnics, 48, 9-20.

Vytiniotis, Antonios, and Andrew J. Whittle. “Effectiveness of PV Drains for Mitigating Earthquake-Induced Deformations in Sandy Slopes.”Geo-Congress 2013.American Society of Civil Engineers, 2013. 908–917

Wieczorek G.F., Larsen M.C., Eaton L.S., Morgan B.A., and Blair J.L. (2002) “Debris-flow and flooding hazards associated with the December 1999 storm in coastal Venezuela and strategies for mitigation”, U.S. Geological Survey.

Yagi, N., and Yatabe, R. (1987) “Prediction method of slope failure in sandy soil due to rainfall”, Proceedings, 8th Asian Regional Conference on Soil Mechanics and Foundation Engineering, Kyoto, pp 217-220.

Yokota, S., Iwamatsu, A., Imura, R., Matsuyuki, K., and Ohkawa, T. (2000) “A new warning index for debris flows based on rainfall and groundwater depth”, Proceedings, GeoEng2000: An International Conference on Geotechnical and Geological Engineering, Melbourne.