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Performance of an instrumented slope covered with shrubs and deep-rooted grass

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Abstract

Green technology, an integrated design approach that combines vegetation and engineering design methods, can be applied to improve slope stability. Orange Jasmine is a small tropical evergreen shrub which has deep root systems and is considered to be a drought-tolerant plant that adapts well to a wide range of climatic and soil conditions. It can also grow in infertile soils, limestone soils or loam. Vetiver grass has been widely cultivated in many tropical and subtropical regions of the world for soil and water conservation, land rehabilitation, and embankment stabilization. Vetiver grass has deep roots (2–4 m) and adapts well under extreme conditions of temperature, soil, moisture, soil acidity, and alkalinity. The role of Orange Jasmine and Vetiver grass in minimizing rainwater infiltration, for improving the stability of slopes, was investigated on a soil slope in Singapore with its tropical climate. Two slope sections, covered with Orange Jasmine and Vetiver grass, were instrumented with tensiometers, installed at different depths within the slope, and a rainfall gauge. The instruments were connected to a real-time monitoring system to study the pore-water pressure, the rainfall, and the groundwater level in the slope throughout a one-year period. The pore-water pressure characteristics within the slope sections covered with Orange Jasmine and Vetiver grass are analyzed and presented in this paper. The analyses indicate that both Orange Jasmine and Vetiver grass played a significant role in reducing rainwater infiltration into the slope, minimizing the loss of matric suction, and hence, the shear strength of the soil during rainfall and, as a result, maintained the stability of the slope. Vetiver grass and Orange Jasmine appeared to be similar in effectiveness in terms of reducing the rainwater infiltration into the slope.

Keywords: Vetiver grass; Orange Jasmine; Slope stability; Rain; Infiltration; Tropical; Instrumentation; Matric suction

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1. Introduction

Rainfall-induced slope failures occur in response to climatic changes in many parts of the world (Jeng and Lin, 2011; Kawamura and Murab, 2013; Kitamura and Sako, 2010; Zhang et al., 2011). Many of the slope failures constitute socio-economic problems caused by the resulting damage and destruction to infrastructures and agricultural lands. Therefore, it is important to have a preventive measure for slopes that are prone to failure due to rainfall. One possible preventive measure for rainfall-induced slope failures is the use of green technology.

Green technology is an integrated design approach that combines vegetation and engineering design methods to mechanically reinforce slopes, to control erosion, to improve the aesthetics of the environment, to provide visual and noise barriers, and to improve biological diversity (Woods, 1938; VanDersal, 1938; Marchent and Sherlock, 1984; Greenway, 1987; Coppin and Richards, 1990; Menashe, 1993; Meyers, 1993; Greenwood et al., 2007; Norris et al., 2008; Schwarz et al., 2009; Glendinning et al., 2009; Ali et al., 2012). Gray and Leiser (1982) summarized several benefits of woody vegetation, such as root reinforcement, soil moisture modification, buttressing and arching, and increased stability brought about by the surcharge or the weight of the vegetation. Zeimer (1981) showed that the strength of the soil increased linearly as the root biomass increased. Zeimer (1981) also reported that live bush roots were twice as strong as conifer roots of the same size. Zeimer and Swanston (1977) found that roots add strength to the soil by vertically anchoring through the soil mass in the bedrock and by laterally tying the slope together across zones of instability.

Orange Jasmine, *Murraya exotica L.*, is also known as mock orange, satin wood, honey bush, China-box, café de la India, mirto, azahar, naranjo, jazmin, limonaria, and bun (Little et al., 1974). It is a small tropical evergreen shrub which can grow up to 7 m tall and 13 cm in stem diameter, and flowers throughout the year. It has white fragrant flowers and glossy leaves, and is grown as an ornamental tree or hedge. Its stems are supported by taproots with lateral roots and a mesh of fine roots. Seedlings quickly develop deep root systems (Francis, 2003) and grow at a moderate rate. Orange Jasmine has a typical life span of at least 15 years and needs little care. Orange Jasmine can adapt to a wide range of conditions. For example, it can be found in Puerto Rico where it grows in areas with about 750–1900 mm of annual precipitation and from nearly sea level to elevations of 1300 m (Neal, 1965). It is native of China, South and Southeast Asia, and Australasia.

Vetiver grass, also known as *Chrysopogon zizaniodes*, is a perennial grass of the Poaceac family from India. Vetiver has been widely planted in many tropical and subtropical regions of the world for soil and water preservation, land rehabilitation, and embankment stabilization. It has been used in Brazil (Grimshaw, 1994), Fiji (Truoung and Gawander, 1996), Malaysia (World Bank, 1995), the West Indies, and South Africa (National Research Council, 1993). Vetiver grass has deep roots, about 2–4 m in depth, that collect water and provide reinforcement to slopes. It is highly tolerant of extreme conditions such as temperature (from −10° to 48 °C in Australia), soil moisture, soil acidity, and alkalinity (pH from 3.3 to 10.5).

When the roots interact with the soil in which it is grown, a new composite material comprising roots with high tensile strength is formed. The shear strength of the soil is enhanced by the root matrix (Styczen and Morgan, 1995). In this paper, the effect of Orange Jasmine and Vetiver grass in increasing the shear strength of soil and in minimizing rainwater infiltration, for maintaining the stability of slopes during rainfall, was investigated on a soil slope in Singapore with its tropical climate.

2. Site description

Old Alluvium covers an area of 7200 ha, or about 15% of Singapore, and can be found in the eastern and northwestern areas. The soils are the result of rapid deposition by a braided river system of weathered materials from slopes of granite and low grade metamorphic rock from Malaysia (Gobbett and Hutchison, 1973; Stauffer, 1973; PWD, 1976). Old Alluvium comprises sand, gravel, silt, and clay, but mainly silty and clayey sand with a fines content of about 20–30%. The color varies from white, yellow, red, and brown to mixtures of these colors (Ni et al., 2006).

A slope located in Old Alluvium, which had no prior record of slope failure, was chosen for the construction of the green technology slope. One portion of the slope (50 m^2) was covered with Orange Jasmine, another portion of the slope (50 m^2) was covered with Vetiver grass, and another portion of the slope was the original slope with cow grass cover. The slope has a height of 8.2 m, a length of 22.6 m, and a slope angle of 20°. The slope is shown in Fig. 1.

3. Design of slope and field instrumentation

Orange Jasmine and Vetiver grass were planted in June and September 2009, respectively. The slope was excavated to a depth of 200 mm below the top soil surface, as shown in Fig. 1. The study area was demarcated by a trench for the insertion of aluminum impermeable walls and for the

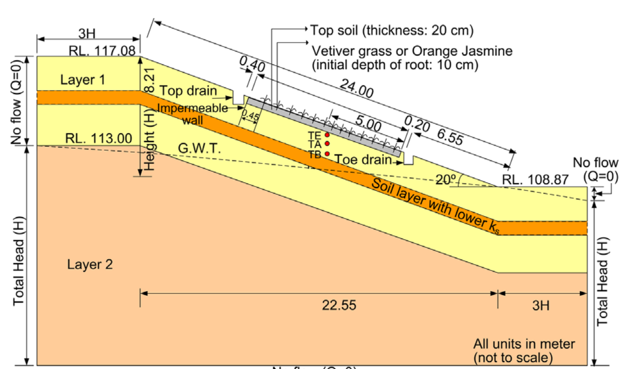

Fig. 1. Schematic diagram of slope with Orange Jasmine and Vetiver grass.

construction of surface drains at the top, the sides, and the toe of the slope. The impermeable walls were installed to a depth of 600 mm from the slope surface to impede the lateral water flow from the surrounding soil into the investigated area (slopes planted with Orange Jasmine and Vetiver grass). The lateral water flow from the surrounding soil into the vegetation area must be excluded, since this study only focuses on the effect of vegetation on slope stability due to rainwater infiltration. The slope within the study area was backfilled and compacted to the original slope surface level with a new top soil. An erosion control blanket mat was laid on the slope surface before planting the Orange Jasmine and the Vetiver grass. This mat was used to protect the slope within the study area from erosion during rainfall. The Orange Jasmine was planted with a lateral spacing of 450 mm and a downslope spacing of 450 mm. The Vertiver grass was planted with a lateral spacing of 250 mm and a downslope spacing of 450 mm. This spacing was sufficient for avoiding the overlapping of root growth between adjacent vegetation. The Orange Jasmine and Vetiver grass slope sections are shown in Fig. 2. The adjacent original slope section, covered with cow grass, was used as a control to study the performance and the effectiveness of the sections covered with Orange Jasmine and Vetiver grass in reducing rainwater infiltration and in maintaining negative pore-water pressure in the slope.

Nine tensiometers were installed in the middle of the slope. Three tensiometers were located in the original slope, three tensiometers in the Orange Jasmine area, and three tensiometers in the Vetiver grass area. The tensiometers installed in the original slope area were named TA3, TB3, and TD3 with a spacing of 0.5 m and insertion depths of 0.67 m, 1.29 m, and 1.84 m, respectively (Figs. 1 and 2). The tensiometers installed in the Orange Jasmine area were named TE4, TA4, and TB4 with a spacing of 0.5 m and insertion depths of 0.4 m, 0.66 m, and 1.21 m, respectively (Figs. 1 and 2). The tensiometers installed in the Vetiver grass area were named TE5, TA5, and TB5 with a spacing of 0.5 m and insertion depths of 0.4 m, 0.67 m, and 1.24 m, respectively (Figs. 1 and 2).

Three Casagrande piezometers were installed at the crest, the middle, and the toe of the slope to measure the level of the

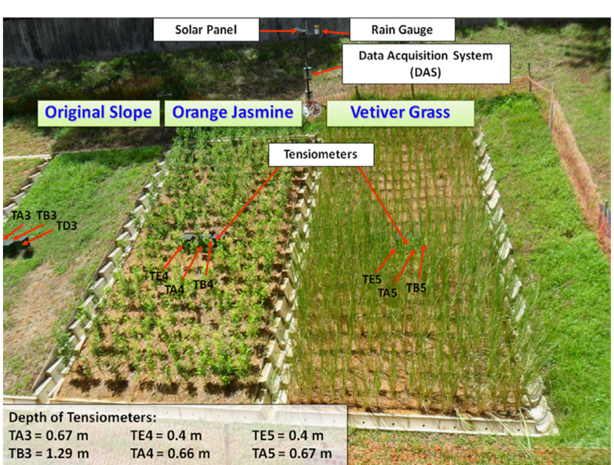

Fig. 2. Layout of instrumented slope.

groundwater table. A tipping bucket rainfall gauge was used to determine the amount of rainfall at the site. A photovoltaic power supply system, consisting of one solar panel module and several reserve batteries for storing energy, was installed on the crest of the slope. All transducers from the tensiometers, the piezometers, and the rain gauge were connected to the same power supply and data logger to obtain the readings in real time which can be accessed on-line.

4. Soil properties

The boreholes within the study area were advanced using rotary boring, with foam as the drilling fluid, to obtain high quality undisturbed soil samples. The undisturbed samples were taken continuously using a Mazier sampler until the required depth of boreholes. Soils with roots were sampled directly beneath the ground surface with vegetative cover (Orange Jasmine or Vetiver grass). The vegetation above the ground surface was removed prior to the soil sampling within the sections of Orange Jasmine and Vetiver. All undisturbed samples were kept inside sealed PVC tubes and brought to the laboratory for soil testing. In the laboratory, the soil samples were extracted with a mechanical extruder. The soil samples were handled carefully to preserve the in-situ condition of the soils with their roots. The soil samples were trimmed to be 10 cm in length and 5 cm in diameter, wrapped in plastic sheets and then aluminum foil, coated with a layer of wax, and stored inside a moist room before soil testing in order to maintain their original water content. Prior to each saturated and unsaturated soil test, the dry density and the water content of each soil specimen were determined to ensure uniformity of all the undisturbed specimens used in the tests.

Index and engineering property tests were carried out to obtain the index properties, SWCC, the saturated and unsaturated permeabilities, and the shear strength of the soil specimens. In addition, organic content tests were conducted to quantify the amount of roots within the soil specimens according to ASTM F1647-11, 2011. The index properties of the investigated soils and the results of the organic content tests are summarized in Table 1. Table 1 shows that the soil samples taken from the slope sections without vegetation contain no organic content, whereas the soil samples taken from the slope sections with Orange Jasmine and Vetiver grass contain organic contents of 6.5% and 12.3%, respectively. These results indicate the presence of roots for the soil samples taken from the areas with vegetation.

Soil–water characteristic curves (SWCCs) were determined by combining the results of Tempe cell tests (for matric suction up to 100 kPa) and pressure plate tests (for matric suction up to 1500 kPa). Matric suction was applied to the specimens in the SWCC tests using the axis translation technique (Hilf, 1956). Details and the procedure of the SWCC tests can be found in Fredlund et al. (2012). Figs. 3 and 4 show the soil–water characteristic curves (SWCCs) and the permeability functions, respectively, of the soils and the original soil with roots. Leong and Rahardjo (1997) reviewed several equations for fitting SWCC and concluded that Fredlund and Xing's equation (Fredlund and Xing,

Table 1
Basic properties of soils.

Description	Soils				
	Layer 1	Layer 1 (with lower k_s)	Layer 2	Orange Jasmine root and layer 1 mixture (OJL1)	Vetiver root and layer 1 mixture (VGL1)
Unified Soil Classification System, USCS	SP	SP	SP	SP	SP
Specific gravity, G_s	2.66	2.66	2.61	2.71	2.64
Water content (%)	21.1	16.8	25.8	19.2	17.2
Gravel content (> 4.75 mm; %)	3.3	4.1	14.2	0.02	11.9
Sand (%)	93.5	93.4	84.4	98.08	85.7
Fines (< 0.075 mm; %)	3.2	2.5	1.4	1.9	2.4
Grain size distribution					
D_{60} (mm)	1.4	1.5	2.2	1.2	1.1
D_{30} (mm)	0.47	0.55	0.95	0.55	0.5
D_{10} (mm)	0.18	0.23	0.4	0.22	0.23
Coefficient of uniformity, C_u	7.78	6.52	5.5	5.45	4.89
Coefficient of curvature, C_c	0.88	0.88	1.03	1.15	1.01
Dry density, ρ_d (Mg/m^3)	1.31	1.73	1.5	1.43	1.86
Void ratio, e	0.77	0.57	1.02	0.20	0.4
Saturated coefficient of permeability, k_s (m/s)	8.7×10^{-5}	6.4×10^{-7}	5.1×10^{-5}	1.08×10^{-5}	2.6×10^{-5}
Organic content (%)	0	0	0	6.5	12.3

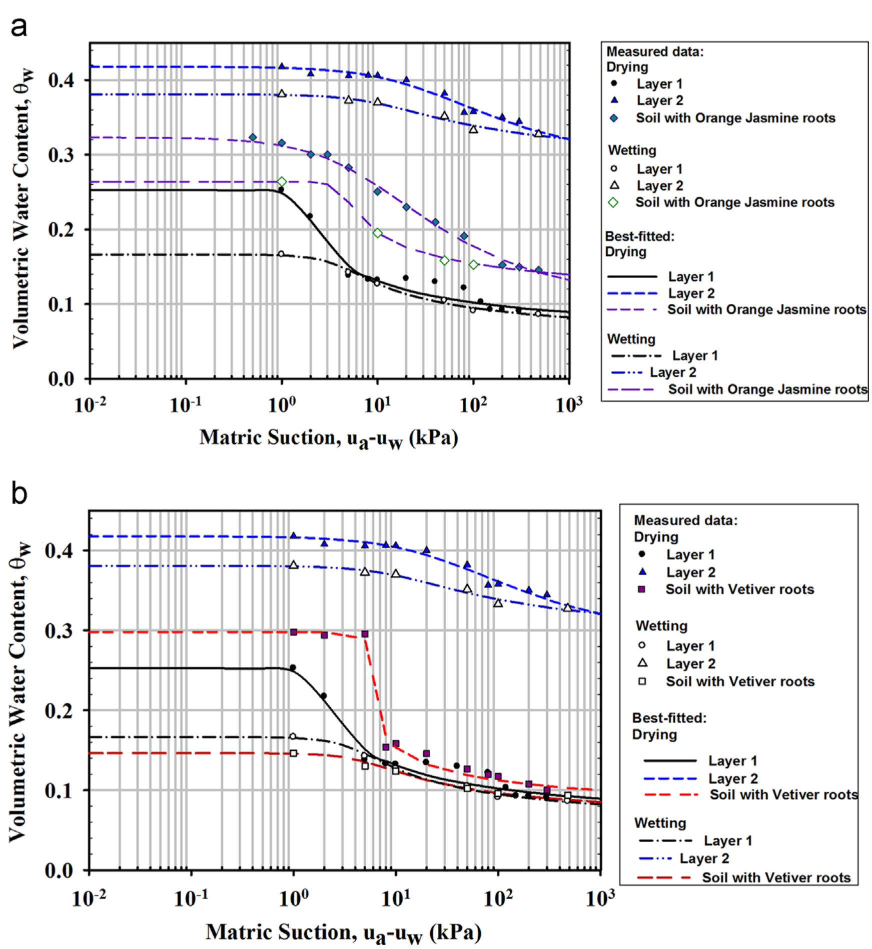

Fig. 3. Soil–water characteristic curves for residual soils and: (a) soil with Orange Jasmine roots and (b) soil with Vetiver roots.

1994) gave the best fit among all the equations. However, Leong and Rahardjo (1997) suggested to use a correction factor of 1 for fitting the SWCC of soils in Singapore. Therefore, the drying and wetting SWCCs of the soils in the slope were best-fitted using Fredlund and Xing's equation (1994) with a correction factor of 1, as suggested by Leong and Rahardjo (1997).

The parameters of Fredlund and Xing's SWCC equation (1994) for the soils are presented in Table 2. The measured saturated permeabilities of layer 1, layer 2, layer 1 with Orange Jasmine roots, and layer 1 with Vetiver roots were 8.7×10^{-5}, 5×10^{-5}, 1.08×10^{-5}, and 2.6×10^{-5} m/s, respectively. The statistical method (Fredlund and Rahardjo, 1993) was used to obtain the permeability functions from the wetting SWCCs of the soils, as shown in Fig. 4. The results of the laboratory tests indicate that the original soil within the investigated area could be divided into two layers. Layer 1 was encountered to a depth of 5 m from the slope surface (Fig. 1).

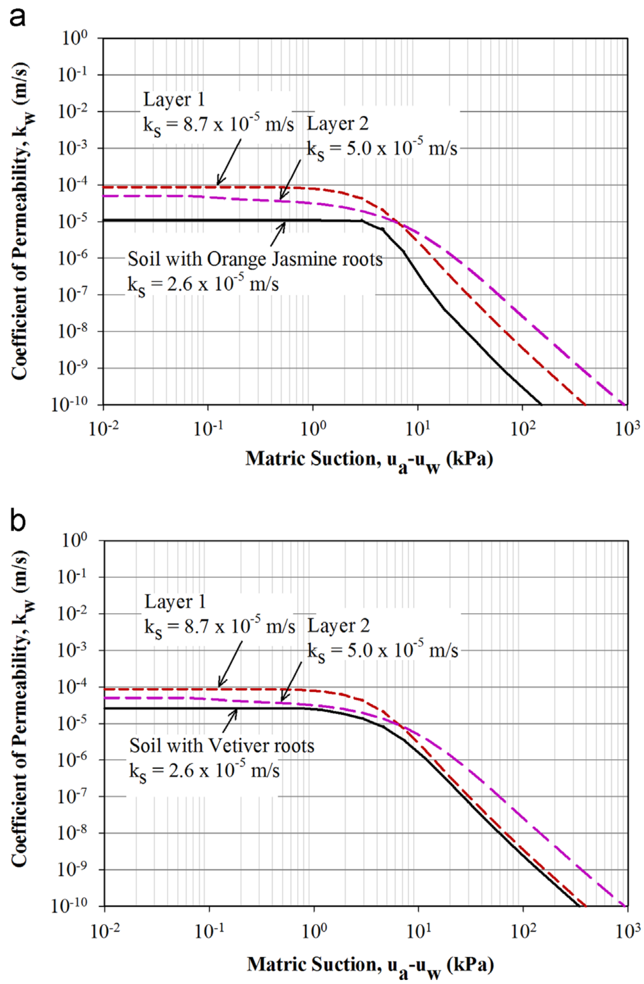

Fig. 4. Permeability functinos for residual soils and: (a) soil with Orange Jasmine roots and (b) soil with Vetiver roots.

5. Effects of Orange Jasmine and Vetiver grass on shear strength of the soils

Triaxial tests were conducted on saturated specimens under effective confining pressures (σ_3-u_w) of 25 kPa, 50 kPa, and 75 kPa; the Mohr–Coulomb failure envelopes are plotted in Fig. 5. Triaxial tests on unsaturated specimens were carried out under a constant net confining stress and at different matric suctions. Each soil specimen of the original soil was sheared under a net confining pressure of 50 kPa and matric suctions of 25 kPa, 50 kPa, and 75 kPa. Each soil specimen with Orange Jasmine or Vetiver grass was sheared under a net confining pressure of 50 kPa and matric suctions of 25 kPa, 50 kPa, and 100 kPa. Typical results from the consolidated drained triaxial tests on unsaturated specimens are shown in Fig. 6. The stress strain curves obtained from the multistage tests carried out in this study indicate that peak shear strength was reached in all stages. It is observed that the Orange Jasmine and Vetiver grass roots showed ductile behavior, as shown in Fig. 6(c) and (d), respectively. They can undergo large deformations prior to failure. Table 3 indicates a significant increase in c' caused by the presence of roots in the soil. The c' values for the soils containing roots of Orange Jasmine and Vetiver grass were found to be higher than the value for layer 1 of the original soil. The ϕ' for the soil with roots of Orange Jasmine is the same as that for layer 1 of the original soil, while the soil with roots of Vetiver grass exhibits a higher ϕ' value than that of layer 1 of the original

Table 2
Hydraulic properties of the materials used in the slope.

Description	Symbol (Unit)	Soils			
		Layer 1	Layer 2	OJL1	VGL1
Drying curve					
Saturated volumetric water content	θ_s	0.32	0.40	0.32	0.37
Air-entry value	ψ_a (kPa)	1	12	1.8	5.5
Residual matric suction	ψ_r (kPa)	9	600	350	8.5
Residual volumetric water content	θ_r	0.11	0.34	0.13	0.13
Fredlund and Xing fitting parameters	a (kPa)	1.55	16.6	5.61	5.12
	n	4.42	1.02	0.98	35.58
	m	0.31	0.19	0.55	0.21
Wetting curve					
Water-entry value	ψ_w (kPa)	30	200	22	40
Volumetric water content at ψ_w	θ_w	0.1	0.33	0.15	0.10
Fredlund and Xing fitting parameters	a (kPa)	3.41	7.47	4	4.31
	n	2.20	1.41	5.42	2.0
	m	0.28	0.09	0.19	0.23

soil. Table 3 also shows that the contribution of the Orange Jasmine roots was more consistent than that of the Vetiver roots on the unsaturated shear strength of soils. The unsaturated shear strength characteristics of the soil with Orange Jasmine roots was linear from low matric suction up to high matric suction, whereas the unsaturated shear strength characteristics of the soil with Vetiver roots started to decrease at matric suction higher than 25 kPa. These results indicate that Orange Jasmine roots could survive longer under dry conditions than Vetiver grass roots.

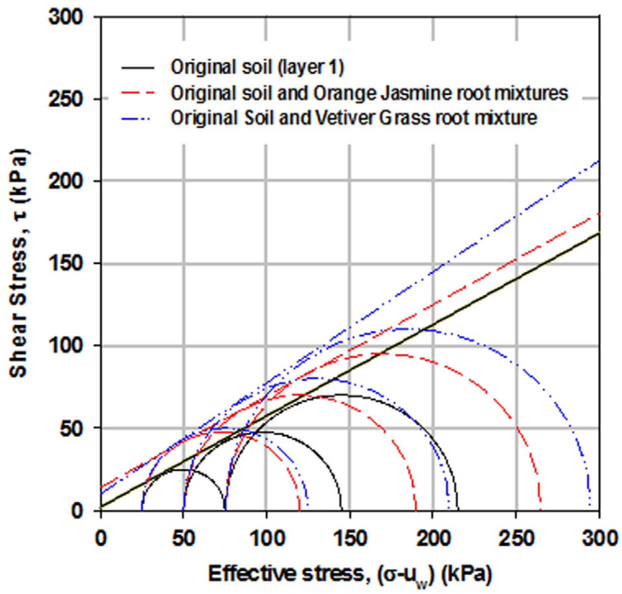

Fig. 5. Mohr–Coulomb failure envelopes at zero matric suction of original soil (layer 1), soil with Orange Jasmine, and Vetiver grass roots.

6. Monitoring results

Fig. 7 presents the groundwater level and the daily rainfall versus time. Fig. 8(a)–(c) shows the pore-water pressure measurements at various depths of the original slope, the slope section with Orange Jasmine, and the slope section with Vetiver grass. Fig. 8(e) shows the rainfall data from 29 July 2010 to 5 January 2011. In the original slope, the pore-water pressure measurements remained negative down to −10 kPa at a depth of 0.67 m from the ground surface during the dry season. However, the original slope could not maintain the negative pore-water pressure during rainfall and even went to positive pressure at deeper depths, i.e., 1.29 and 1.84 m from the ground surface. There was a possibility of water accumulation above layer 1 with a lower permeability (6.4×10^{-7} m/s) along the slope at a depth of 1.5–2.1 m from the ground surface (Fig. 1). In the Orange Jasmine area, the negative pore-water pressure could be maintained down to −5 kPa at a depth of 0.4 m from the ground surface during the dry season. In the Vetiver grass area, the negative pore-water pressure could be maintained down to −15 kPa at a depth of

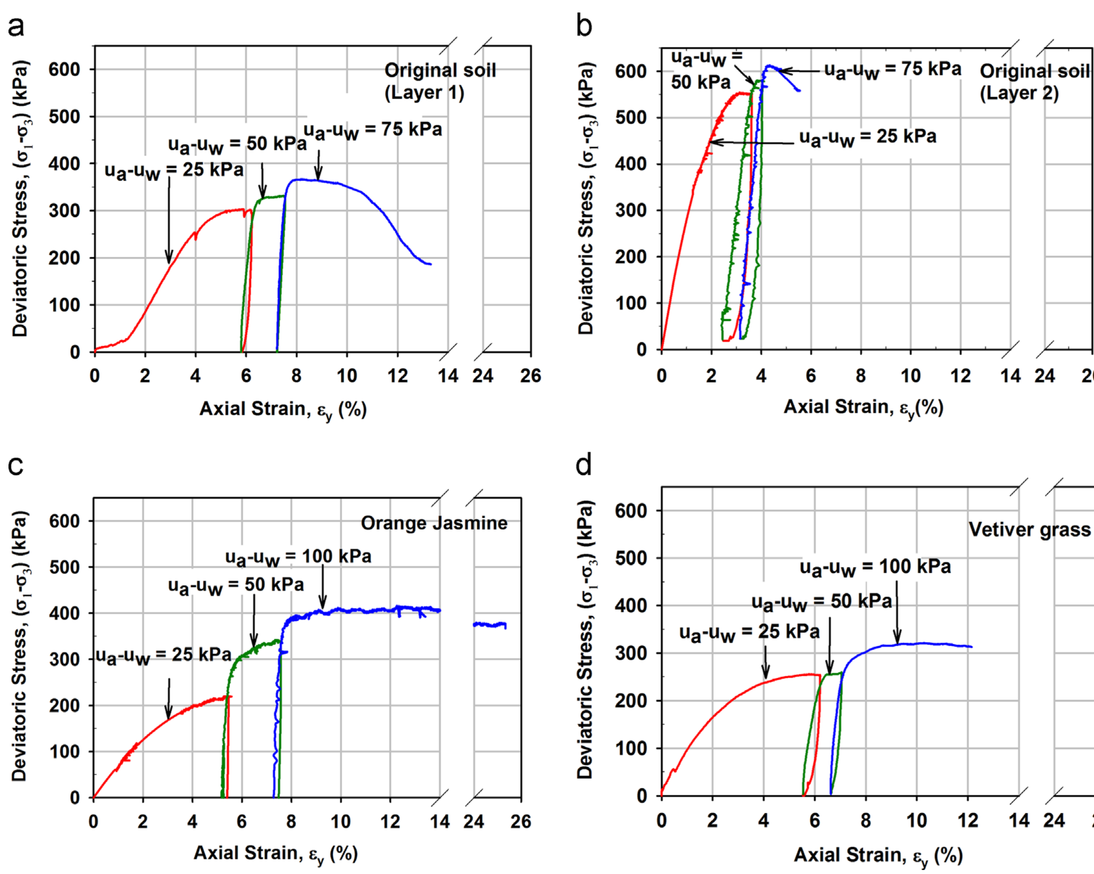

Fig. 6. Deviatoric stress versus axial strain curves of: (a) original soil (layer 1), (b) original soil (layer 2), (c) soil with Orange Jasmine roots, and (d) soil with Vetiver grass roots.

Table 3
Shear strength properties of soils.

Description	Symbol	Soils			
	(Unit)	Layer 1	Layer 2	OJL1	VGL1
Unit weight	γ (kN/m^3)	15.5	18.5	21.7	21.4
Effective cohesion	c' (kPa)	2	5	14	10
Effective friction angle	ϕ' (deg)	29	37	29	34
Air-entry value	ψ_a (kPa)	1	12	1.8	5.5
ϕ^b for $0 < (u_a - u_w) \leq 25$ kPa	ϕ^b (deg)	29	37	29	34
ϕ^b for $(u_a - u_w) > 25$ kPa	ϕ^b (deg)	21	18	29	19

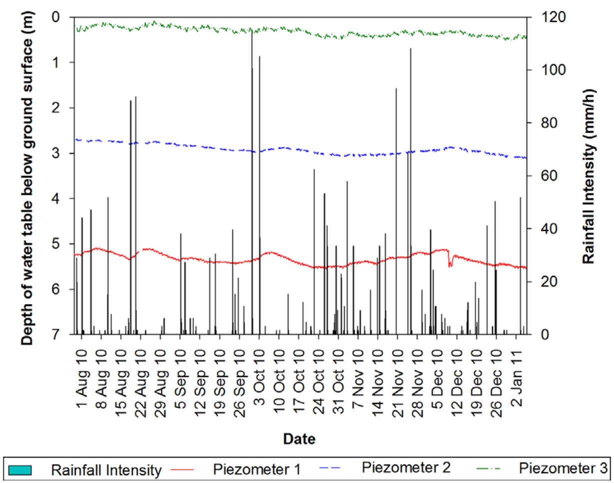

Fig. 7. Groundwater level and daily rainfall versus time.

1.12 m from the ground surface during the dry season. Generally, higher negative pore-water pressures existed in the Vetiver grass area than those in the Orange Jasmine area. This could be attributed to the higher amount of roots in the Vetiver grass area as compared to that in the Orange Jasmine area, as shown by the organic content test results (Table 1). However, both areas were able to preserve the negative pore-water pressure well during rainfall.

7. Slope stability analyses

Slope stability analyses using Slope/W (GEO-SLOPE International Ltd., 2007) were performed for the typical slope model presented in Fig. 1 with the Bishop's simplified method of slices. The "total cohesion" method was used to analyze the stability of the original slope and the slope sections covered with Orange Jasmine and Vetiver grass. In the model, the soil layers were divided into several sub-layers. The effect of rainwater infiltration on the matric suction was reflected by the change in total cohesion in each layer. The total cohesion was obtained from the summation of the effective cohesion and the shear strength contribution due to the matric suction (i.e., $(u_a - u_w)\tan \phi^b$) (Fredlund et al., 2012). The change in matric suction was obtained from the pore-water pressure measured during the period from 29 July 2010 to 5 January 2011 at Tampines. The soil shear strength parameters used in the slope stability analyses are summarized in Table 3. The variations in soil cohesion were incorporated in Slope/W to obtain the variation in factors of safety for the original slope and the slope sections covered with Orange Jasmine and Vetiver grass during and after rainfall. The soils with the roots were represented as a soil layer with a depth of 10 cm to 1 m from the ground surface, and the material properties of the soils containing Orange Jasmine or Vetiver grass roots were assigned to this particular layer. Fig. 8(d) shows the variation in factors of safety in relation to the rainfall events during the period from 29 July 2010 to 5 January 2011. The factors of safety of the areas covered with Orange Jasmine and Vetiver grass were relatively higher than those of the area of the original slope during rainfall events, indicating the effectiveness of the vegetative covers in minimizing rainwater infiltration into the slope.

Slope stability analyses of the original slope and the slope sections covered with Orange Jasmine and Vetiver grass have been performed for a rainfall intensity of 22.2 mm/h that occurs continuously for 1 day based on a 25-year return period. Fig. 9 shows the results of the slope stability analyses. The original slope has an initial factor of safety of 2.47 before the rainfall and drops significantly to a factor of safety of 1.83 after 24 h of rainfall. The initial factors of safety for the areas covered with Orange Jasmine and Vetiver grass before the rainfall are 2.53 and 2.41, respectively. The factors of safety for the areas covered with Orange Jasmine and Vetiver grass decrease slightly to minimum factors of safety of 2.38 and 2.26, respectively, after 24 h of rainfall. This indicates that the factors of safety for both slopes covered with vegetation remain high after 24 h of rainfall. The lower rates of changes in factors of safety for the slopes covered with vegetation, as compared to those of the original slope during rainfall, illustrate the effectiveness of vegetation as a slope cover in maintaining the stability of slopes during severe rainfall events. In addition, the rate of changes in the factors of safety for the slope sections covered with Vetiver and Orange Jasmine are the same (Fig. 9), indicating that Vetiver grass and Orange Jasmine were similar in effectiveness in terms of reducing rainwater infiltration into the slope.

8. Conclusion

The laboratory tests and field monitoring results show that both Orange Jasmine and Vetiver grass can be used as slope covers to minimize the infiltration of rainwater into slopes. The results of shear strength tests indicate that the presence of roots increases the effective cohesion of the original soil, resulting in the increase in shear strength of the soil covered with

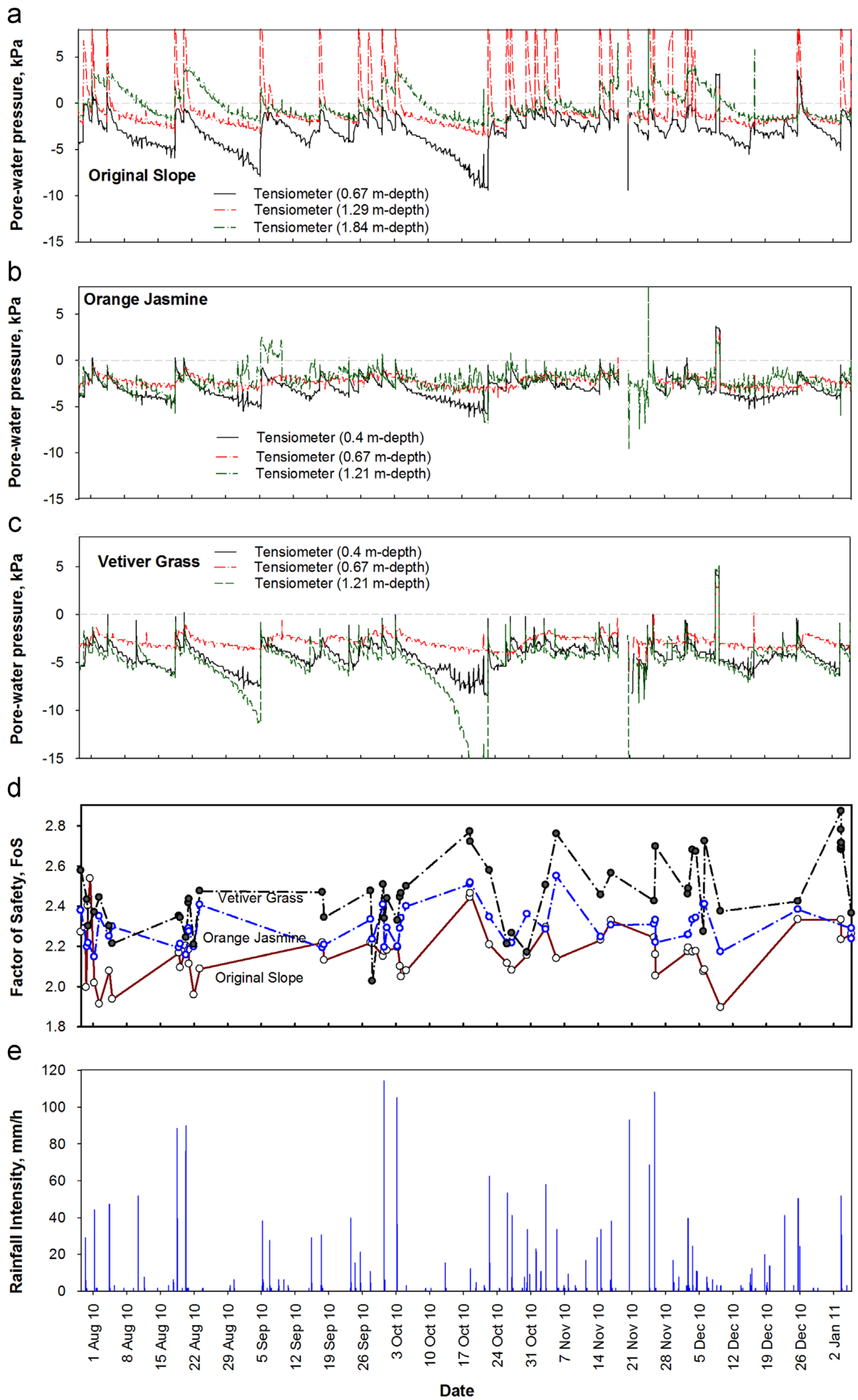

Fig. 8. Pore-water pressure measurement at various depths of: (a) original slope, (b) the slope with Orange Jasmine, (c) the slope with Vetiver grass, (d) factor of safety variation and (e) rainfall intensity from 7/29/2010 12:00 to 1/5/2011 17:50.

vegetation. The field monitoring results show that Orange Jasmine and Vetiver grass covers were able to maintain the negative pore-water pressure within the slopes during rainfall. In other words, vegetation is an effective slope cover for maintaining the stability of slopes during rainfall. In addition, Vetiver grass and Orange Jasmine appeared to be similar in

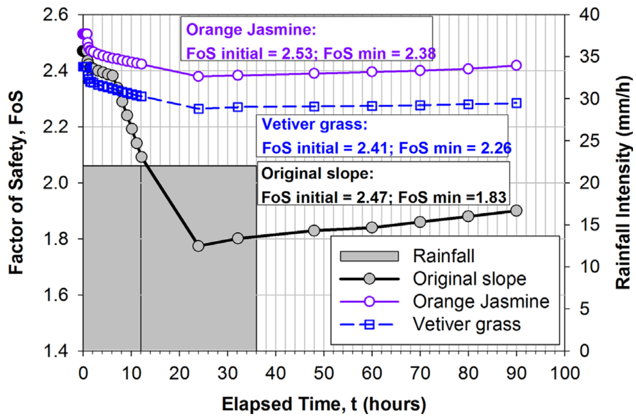

Fig. 9. Factor of safety variations of slopes for 1 day rainfall intensity of 22.2 mm/h.

effectiveness in terms of reducing rainwater infiltration into the slope.

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