Rainfall-induced landslide stability analysis in response to transient pore pressure

——A case study of natural terrain landslide in Hong Kong

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Abstract Transient pore pressure in response to short intense rainfall process plays an important role in shallow landslide occurrence. Using GIS technology, we carry out the rainfall-induced landslide stability analysis in response to transient pore pressure by means of transient and unsaturated rainfall infiltration modeling. A case study is performed on the shallow landslide stability analysis in Hong Kong. Detailed analysis and discussion reached some useful conclusions on the tempo-spatial behavior and characteristics of slope stability response and pore pressure response to typical rainfall process. Comparison analysis is performed on some important issues including landslide stability response in different types of slopes with different hydraulic properties, antecedent rainfall and landslide stability, and the nature of pore pressure response time. These studies might give us an important insight into landslide tringgering mechanism and the hydrological process in response to rainfall, and provide systematic information and evidences for effective risk assessment and warning system establishment.

Keywords: *rainfall-induced landslide, transient pore pressure, landslide stability in response to rainfall, GIS.*

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Rainfall or rainstorm is one of the most significant triggering factors for landslide occurrence. Study of rainfall-induced landslide mechanics is one of the most important and difficult issues for landslide research[1]. In general, the effect of rainfall infiltration on slope could result in changing soil suction and positive pore pressure, or main water table, as well as raising soil unit weight, reducing anti-shear strength of rock and soil[2—14].

However, different types of landslide perform different behaviors in response to rainfall process. For deep seated landslides, their stability states are mostly affected by the rising of main water table and rock and soil softening by rainfall infiltration. For shallow landslides, their stability behaviors and styles are dominated by transient pore pressure in response to rainfall process, combined with water washing or soil erosion. For example, landslips in Hong Kong are characterized by shallow landsliding or slump in saprolite and colluviums. Sliding plane is usually composed of relic structures and interlayer between different weathered layers with a depth less than 2 m. The rising of main water table affected by rainfall hardly exceeds the location of sliding plane. So the slope stability in Hong Kong is primarily controlled by transient pore pressure in response to short intense rainfall process and slightly affected by main water table rising[15–20]. Therefore the study of rainfall-induced landslide stability in response to transient pore pressure is significant for shallow landslide predicting and warning.

Recently, the studies of rainfall-induced landslides mainly focus on statistical analysis of correlation between landslide and rainfall, or experimental description. These methodologies and experimental researches are important, but, they provide no theoretical framework for understanding the slope transient pore pressure behaviors in response to rainfall process, and its hydrological and physical process influence on the location, timing, and rates of landslides or for anticipating how landslide hazards might change in response to changing rainfall process[6,7]. Several theoretical models integrated in GIS have been developed based on effective stress principle to depict landslide potential to underground water in discrete landscape cells[21–24]. As for hydrological process modeling, these models usually use steady or quasi-steady flow model to predict the underground water table and assure the groundwater flows exclusively parallel to the slope. They neglect the underground pore pressure redistribution in slope associated with rainfall infiltration for easy implementing model and landslide hazard analysis. But this neglect leads to difficult understanding the fact that the groundwater pressure in hillslopes responds strongly to transient rainfall and that the pore pressure redistribution includes a large component normal to slope[7,23]. A theoretical model was developed by Iverson using rational approximations and unsaturated Richard model to assess the effects of transient rainfall on timing, rate and location of landslides. Combined with infinite-slope stability model, the Iverson's model provides a good approach to evaluate the transient pore pressure effect in response to rainfall and slope failure potential at diverse locations within a landscape by predicting the transient pore pressure head and the factor of safety at any depth of slope over varying period of rainfall[7]. The application of model in some areas has achieved some good results in shallow landslide hazard analysis induced by rainfall[7,25–27].

The main objectives of this paper are to discuss the tempo-spatial characteristics of natural terrain landslide hazard in Hong Kong (especially in Lantau Island area) in response to transient pore pressure triggered by transient rainfall process using Iverson's transient infiltration model. This research might give a good insight in the effect of rainfall process and slope failure mechanism, and provide systematic information and evidences for effective risk assessment and warning system establishment.

1 Study area

Landslides induced by rainfall are most common in the natural terrain slope in Lantau Island. Lantau Island is mainly covered by hilly terrain with average slope angle larger than 15°. The occurrence of landslide and debris flows is highly correlated to rainfall with volume ranging from tens to thousands metric meter. The geology of Lantau Island is composed of volcanic rocks and the younger granitic suite of rock. Severe landslides mainly occur in completely weathered volcanic rocks, and the slope in weathered granitic rocks are slightly affected by landslides and debris flows[17,18,28—30].

Tung Chung East study area is selected based on the following principles (fig. 1): First it could represent the temp-spatial characteristics of rainfall-induced landslide in Lantau Island study area and be convenient for comparison analysis; Second it has close relationship to region development; Third it had a great number of slope failures and finally a great amount of data and references are available.

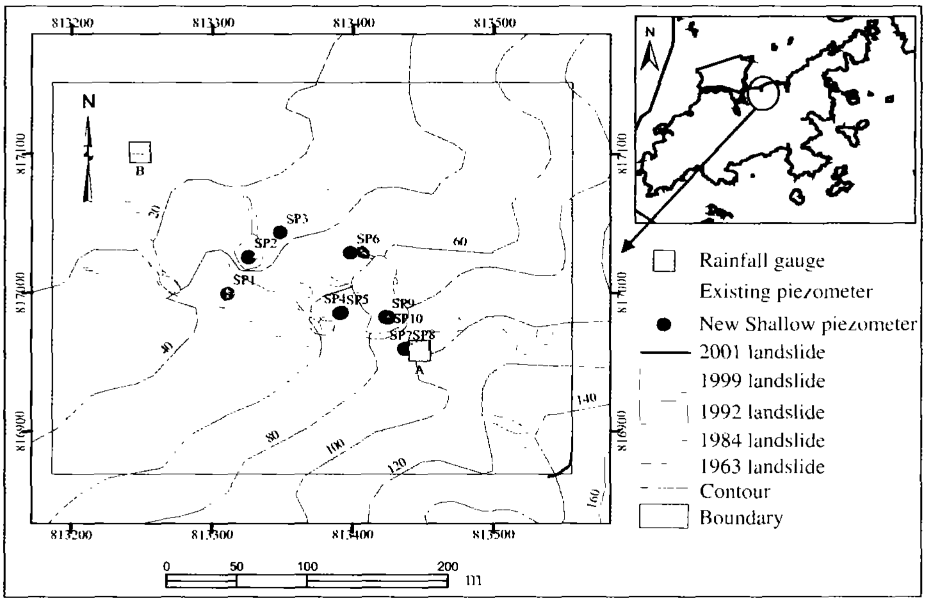

Fig. 1. Tung Chung East study area.

Tung Chung East study area is located east of Tung Chung on Lantau Island, above the North Lantau Expressway. The main geological condition is weathered volcanic rocks with natural slope of 30°—40°. Comprehensive research has been carried on Tung Chung East area and detailed data are available in this site including rainfall data of every 5 min, groundwater pressure monitoring data per hour, geological conditions, ground movement and boreholes data taken in the late 1970s and early 1990s. According to GEO report 4/2002 m[20], the study area has been monitored since the summer of 1999 including seismic survey, trial pits and trench, and shallow boreholes together with dynamic probing. More specific investigation has been performed since August 1999, including surface mapping, installation of surface survey marks and raingauges, sinking of portable sampler holes, installation of piezometer/tensionmeters and instrument of investigating disturbed ground, and laboratory experiments.

Landslides in study area mainly occur in East Lantau Rhyodacite with two failure modes: shallow landslip and slum, which is similar to other areas in Lantau Island. According to aerial photo interpretation and field survey, the main landslides distribution was established shown in fig. 1[20]: before 1963: a variety of landsliding types ranging from minor surface failure to possible slab-slide event; between November 1984 and December 1986: one slump-type high mobility failure; between April 1992 and November 1992: three minor high-mobility surface failures and multi-scale shallow failure, triggered by rainfall July 18—19, 1992, occurred; November 1—11, 1993: multiple failure were observed close to the west of the site; August 22—27, 1999 (Typhoon Sam), large scale slopes failure occurred ranging from shallow low-mobility slab-sliding to high-mobility slump type failures; July 6—8, 2001, one minor surface failure.

2 Main parameters

Table 1 shows the main parameters used in the modeling of landslide stability in response to rainfall. They mainly include physical and mechanical parameter, hydraulic parameters, most of which are varying from cell to cell and retrieved from grid files in GIS.

Table 1 Main parameters

Parameter	Value
Water unit weight γ_w /kN • m^{-3}	9.8
Soil cohesion c/kPa	2
Friction angel φ(°)	38.5
Soil unit weight γ/kN • m^{-3}	19
Max depth of regolith Z_{max}/m	Varying
Initial infiltration rate I_Z /m • s^{-1}	0
Initial underground water table d/m	Varying
Max hydraulic diffusivity D_0/m^2 • s^{-1}	Varying
Saturated hydraulic conductivity K_Z /m • s^{-1}	Varying
Rainfall period N	18

2.1 Rainfall process input

Raingauge A shows that the typical rainstorm with maximum intensity in June 2001 occurred on June 11 in this study area (fig. 2). Pore pressure monitoring data per hour are also available on June 11. The maximum 24-h rainfall was recorded as 209 mm. The rainfall process on June 11 are typified by an initial period of moderate intensity rainfall (about 9 mm/h) contributing 70 mm rainfall. This initial rainfall was then followed immediately by more intense rainfall (82.5 mm/h at 11：00) contributing 120 mm in 2 h. Then the rainfall intensity drops rapidly till the cease of rainfall process. Rainfall process

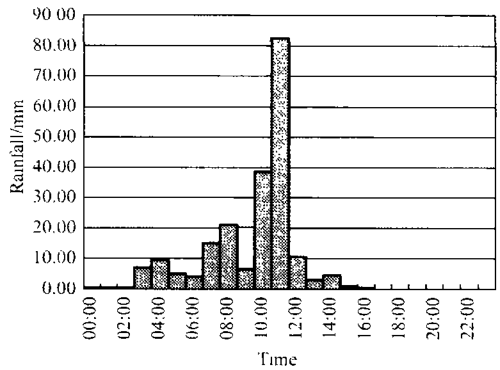

Fig. 2. Rainfall process on June 11, 2001.

is classified into 18 periods by interval of 1 h for the model input. With the neglect of evapotranspiration during the continuous rainfall process, the rainfall intensity per hour is input as the rainfall infiltration rate. Taking the slope runoff during rainfall process into account, when rainfall intensity is larger than the slope saturated hydraulic conductivity, the runoff occurs, the effect of runoff on the next cells might be further infiltration or further runoff to next cells. So the actual cell infiltration rate is the sum of effective rainfall infiltration rate and runoff infiltration rate.

2.2 Maximum depth of regolith (Z_{max})

Evans et al. mapped the thickness of regolith (high weathered soil, residual, colluviums and deposit of debris flow, etc.) in the study area by means of boreholes data comparison, trial pit data analysis, seismic survey and ground conditions observation. We take the thickness of regolith as the maximum depth (Z_{max}) and put it into grid file for calculating.

2.3 Initial underground water table (d)

The distribution initial underground water table in site was constructed by Kriging interpolating of initial underground water table data obtained from 10 monitoring sites located on the southern ridge and debris flow fan, and 7 monitoring sites located at 7 m depth of portable sampler holes (fig. 1).

2.4 Hydraulic parameters(K_Z and D_0)

The hydraulic parameters including hydraulic conductivity and hydraulic diffusivity are very important for modeling process. In addition to referring to the related parameters used in Hong Kong GEO reports, the hydraulic parameters were also optimized by comparing the modeling result of pore pressure with its monitoring value. The final parameters will be defined when the calculated pore pressure curve is very close to monitoring curve under the same rainfall process.

The Tung Chung East study area was well installed with 10 new shallow piezometers developed by Geotechnical Observations Ltd., which can measure pore pressures continuously over range from +65 to −100 kPa. These piezometers are coded from SP1 to SP10 and their locations are shown in fig. 1. The data recording interval of piezometers was set at 1 h for pore pressure monitoring in both disturbed area and undisturbed area. The distribution of hydraulic parameters can be achieved by spatial interpolating of the discrete monitoring data.

For the convenience of comparison analysis, 4 sites in different geological settings were selected. They are SP5 and SP6 in completely deposited volcanic rocks (CDV), SP8 in colluviums (Col) and SP10 in residual soil (Res.). Table 2 shows the major hydraulic parameters of these 4 sites. Among these sites, SP8 has the largest hydraulic conductivity with dimension of 10^{-4} m/s. The conductivity dimension of the other sites is 10^{-6} m/s. SP6 has larger hydraulic conductivity than SP5 owing to the existence of more relic joints.

Table 2 Major hydraulic parameters and soil properties of selected sites

No	SP5	SP6	SP8	SP10
Soil type	completely decomposed volcanic rock (CDV)	completely decomposed volcanic rock (CDV) with more relic joints	colluviums (Col)	residual soil (Res.)
Tip depth/m	1.53	3.0	1.0	1.15
Slope angle/(°)	25.9610	23.3434	32.9540	29.2059
Hydraulic conductivity/m • s^{-1}	1.2×10^{-6}	7.6×10^{-6}	1.5×10^{-4}	1×10^{-6}
Hydraulic diffusivity/m^2 • s^{-1}	8×10^{-4}	1.3×10^{-3}	7×10^{-2}	6×10^{-4}
Initial water table/m	~4.8	~5 m	~3.5 m	~4 m
Ground condition	disturbed	undisturbed	undisturbed	disturbed

In the flowing parts, we will systematically relate the pore pressure characteristics and slope stability behaviors of these 4 sites in response to the rainfall process on June 11, 2001, as well as their detailed comparison analysis.

3 Transient pore pressure in response to rainfall process

3.1 General characteristics

The pore pressure response processes in the above 4 slope sites exhibit some general characteristics. The largest and most rapid pore pressure (positive and negative) response takes place at shallow depths in slopes. Deeper slopes have slow pore pressure changes in response to rainfall process. With the rising of rainfall intensity, the pore pressure at different depths of slope increases gradually to similar magnitude, and finally to peak value. During the finishing period of rainfall, pore pressure declines and soil suctions develop to some extent relying on the slopes permeability. In the slope with low permeability, for example, SP5 and SP10, the pore pressure declines slowly and even keeps on a high value at the end of rainfall process. In the slopes with high permeability, such as SP6 and SP8, pore pressure declines rapidly synchronized with rainfall process. At the end period of rainfall, the soil suction recovers to some extent. The pore pressure response characteristics are also strongly affected by other factors, such as geomorphological and geological conditions.

3.2 Effect of antecedent rainfall

To assess the effect of rainfall process on transient pore pressure in slope, a comparison analysis was performed between modeling result and monitoring result of pore pressure in the four sites on June 11, 2001 (illustrated in fig. 3). The initial infiltration is set to zero to evaluate the effect of antecedent rainfall on pore pressure, which results in the discrepancy of the calculating curve and monitoring curve at the first period of rainfall process. The possible existing of weak permeability layers in some slopes (such as SP8, SP10) leads to that the pore pressure remains at certain value till the end period of rainfall process.

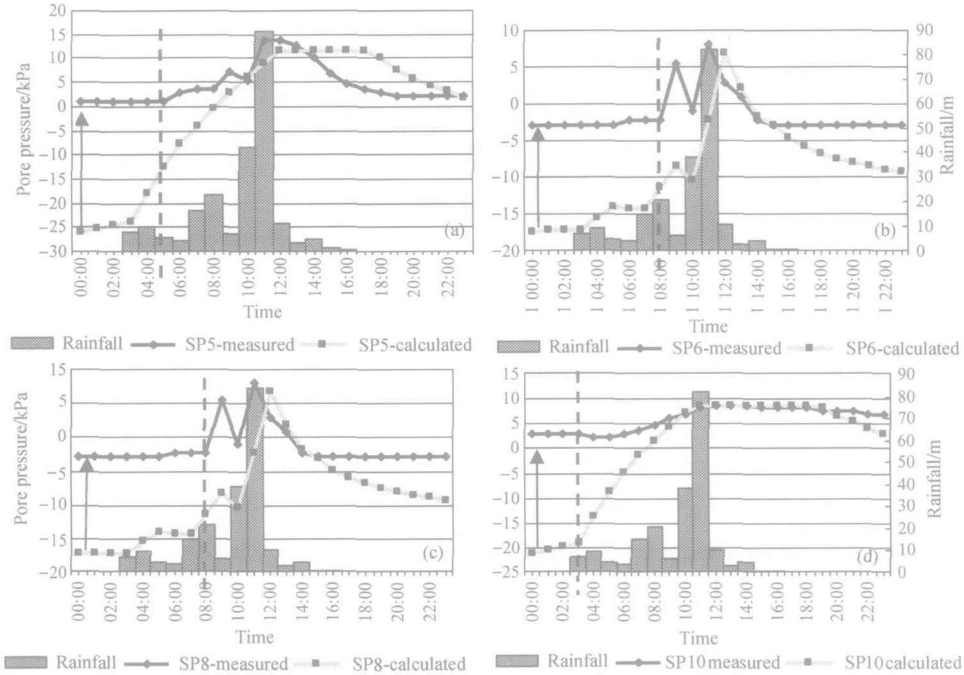

Fig. 3. Transient pore pressure comparison analysis between modeling results and monitoring results. The arrows indicate the loss of soil suction and their lengths show the magnitude. The vertical dash lines exhibit the starting time of transient pore pressure response. The horizontal line of monitoring curve at the end of rainfall indicates the possible existence of weak permeability layer in slopes. (a) SP5 in completely decomposed volcanic slope; (b) SP6 in completely decomposed volcanic slope; (c) SP8 in colluviums slope; (d) SP10 in residual slope.

In general, the antecedent rainfall can cause obvious loss of soil suction (negative pore pressure) or increment of positive pore pressure. The antecedent rainfall during 10 days before June 11, 2001 contributed about 300 mm (30 mm/d) rainfall and destroyed the soil suction ranging from 10 to 25 kPa determined mainly by the depths and permeability of slopes.

The pore pressure affected by antecedent rainfall shows various behavior nature in different slopes. In the shallow completely decomposed volcanic slope (SP5, at 1.53 m depth), antecedent rainfall destroyed its soil suction drastically with the value of about 25 kPa. In this respect, residual soil slope (SP10) showed a similar feature. These two slopes have a similar low permeability and low water storage capability. The saturated condition is easy to be satisfied and causes the complete loss of soil suction. The loss of soil suction at deeper depth in volcanic slope (SP6 at 3.0 m depth) was about 10 kPa, slightly affected by antecedent rainfall, which is similar to that of high permeability slopes, such as 15 kPa of SP8 in colluviums. Their high water storage capability makes it difficult to meet the saturated conditions by antecedent rainfall. With the proceeding of rainfall and increasing of rainfall intensity, the pore pressure was gradually controlled by this period of rainfall process.

In addition to the loss of soil suction, antecedent rainfall may shorten the pore pressure response time and accelerate its response rate.

3.3 Time scale of transient pore pressure response

The dash lines in fig. 3 indicate the possible starting response time of pore pressure in the June 11 rainfall process. Some conclusions can be drawn by means of comparison analysis of response time in different types of slopes. The starting response time of transient pore pressure at the shallow depth of slopes is much shorter than that at deeper depth of slopes, indicating the fast response rate. For example, the starting response time at 1.53 m depth in SP5 and at 1.10 m depth in SP10 is 5 and 3 h respectively from the start of rainfall. At the deeper depth of slopes (for example, SP6 at 3.0 m depth), the starting response time of transient pore pressure is as long as 8 h after the beginning of rainfall. In addition, high permeability slopes have a longer starting response time of transient pore pressure. Although at the shallow depth, the starting response time of pore pressure in SP8 with high permeability is up to 8 h. These high permeability slopes have higher hydraulic conductivity and water storage capacity, so the longer time is needed to lead to obvious pore pressure changes, especially during the start period of rainfall with lower rainfall intensity. The larger rainfall intensity, the shorter time is required for transient pore pressure response. At the peak period of rainfall (82 mm/h), the response time of transient pore pressure to peak rainfall intensity is about 1 h at shallow depth and about 3 h at greater depth (< maximum depth). Therefore, the staring response time of transient pore pressure is a function of slope depth and permeability of slope. It can be estimated that in this study area, the average staring response time of transient pore pressure in the shallow slopes is about 1—5 h, which can be used as the reference for landslide warning.

3.4 Pore pressure response process at depths

Fig. 4 demonstrates the prediction of pore pressure response process at various depths (<5.0 m in this case) of different slopes. The pore pressure response process at low permeability slope and high permeability slope is discussed respectively, especially the effect of permeability of slope on the transient pore pressure process in response to rainfall process.

(i) Pore pressure response in low permeability slope. SP5 in completely decomposed volcanic slope and SP10 in residual slopes have similar low permeability and then similar response process of transient pore pressure during the rainfall. We take SP5 as an example for detailed discussion of pore pressure response process in low permeability slopes (fig. 4(a)).

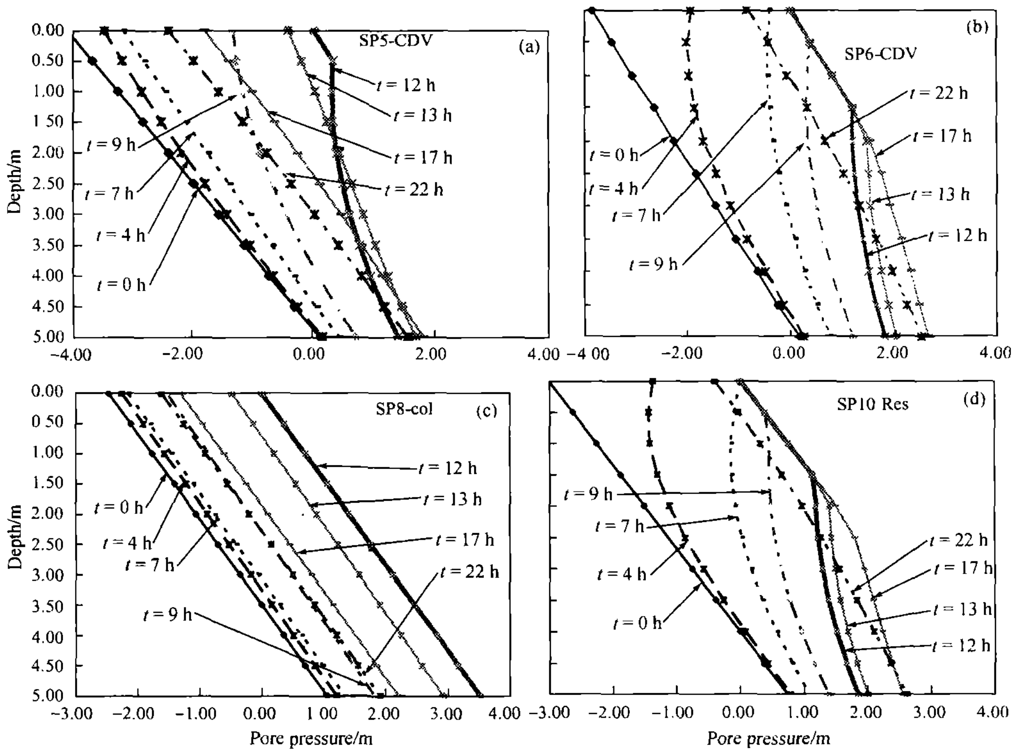

Fig. 4. Transient pore pressure response at the range of depths in different slopes. (a) Low permeability SP5 in CDV; (b) high permeability SP6 in CDV; (c) high permeability SP8 in col; (d) low permeability SP10 in residual soil.

At the beginning period of rainfall (0—3 h), the pore pressure shows no obvious changes at the whole profile owing to the low rainfall intensity.

Rainfall intensity starts to increase obviously at t = 4 h, and the pressure head at different depths demonstrates different developing trends. Much faster pore pressure head response occurs at shallow depth, and the pore pressure head remains unchanged at greater depth. This trend is illustrated by the pore pressure-depth line curving to right remarkably at shallow parts of slope. When the rainfall duration increases, the pore pressure tends to response synchronically at the range of depth. When t = 9 h, the pore pressure head at 0.5 m depth eventually exceeds ultra hydrostatic pressure head, indicating that the slope above 0.5 m depth becomes saturated. Below 0.5 m depth, the pore pressure head curve tends to be vertical, indicating the similar pressure head value at the range of depth. For example, at t = 10 h, the water pressure head at 3.0 m depth is 0.77 m and that at 1 m depth is 0.63 m.

Peak rainfall occurs at t = 11 h with an intensity of 82 mm/h and the saturated zone is up to about 1.5 m in depth. The rainfall intensity declines rapidly at t = 13 h, but the pore pressure head continues to rise, especially at greater depth, indicating the effect of hydrological process in response to rainfall extending to deeper parts of slopes. This tendency remains till the end of rainfall at t = 17 h and the pore pressure at the range of depths achieves the maximum value, showing the maximum effect of rainfall on transient water pressure. Subsequently, the pore pressure declines gradually at the range of depth. The pore pressure head at shallow depth drops slightly faster than that of greater depth.

(ii) Pore pressure response in high permeability slope. The pore pressure response in high permeability slope remarkably demonstrates different characteristics to that in low permeability slope as discussed above. Taking SP6 as an example (fig. 3(b)), at the beginning period of rainfall, the rainfall intensity and rainfall amount are not large enough for obvious pore pressure response. The pore pressure at the range of depths remains unchanged, which is similar to that of low permeability slopes, but keeps longer till to t = 7 h. When t = 8 h, rainfall intensity increases to 21 mm/h, and obvious pore pressure response occurs at the shallow depth, which can be seen from the pore pressure-depth curve at t = 9 h. Rainfall intensity drops to 6.5 mm/h at t = 9 h, which causes the obvious decrease of pore pressure at shallow depth, but has no effect on the greater depth. The response rate of transient pore pressure at shallow depth of high permeability is faster than that of low permeability slope, but needs higher rainfall intensity. The peak rainfall intensity at t = 11 h leads to the remarkable development of water pressure head at shallow depth and the forming of saturated zone above 0.5 m depth. The pore pressure-depth curve at the depth ranging from 0.5 to 2 m becomes vertical, indicating that the pore pressure head at this range of depth remains the same. When t = 13 h, the pore pressure above 2 m depth decreases dramatically, but that below 2 m depth generates continuously. The rainfall intensity declines rapidly after t = 13 h, which leads to the decline of pore pressure at greater depth. At the end period of rainfall (t = 17 h), the pore pressure head above 3.5 m depth exhibits the decreasing tendency, and then the whole range of depth. Soil suction recovers to some extent at the shallow depth. The pore pressure response rates in the process of rainfall are more rapid in SP8 colluviums slope illustrated by a group of almost parallel lines (fig. 4(c)). In contrast to lower permeability slope, the pore pressure affected by rainfall in high permeability slope has higher response rate and greater response depth, but has a shorter operating time.

All of the characteristics discussed above are also clearly illustrated by fig. 5. Under the same rainfall process, high pore pressure head usually forms rapidly in the

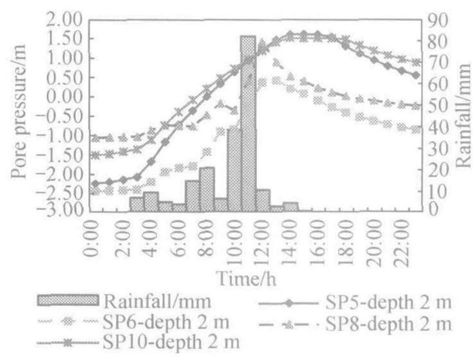

Fig. 5. Comparison analysis of pore pressure response at the same depth (2 m) of different slopes.

shallow slopes with low permeability and declines slowly till the end of rainfall process. In contrast, the pore pressure in the slopes with high permeability responses slowly at the beginning period with low rainfall intensity. When the rainfall intensity increases to certain magnitude, pore pressure responses quickly at greater depth. The pore pressure head declines remarkably at the end period of rainfall. The soil suction develops rapidly.

4 Landslide stability in response to rainfall process

Landslide stability affected by rainfall has close relationship to the water pressure or seepage pressure in response to rainfall process and related geological and geomorphological conditions, physical and mechanical parameters. In the process of transient rainfall, the rainfall infiltration is characterized by vertical infiltration and has slight effect on the geological conditions and physical and mechanical parameters. When rainfall occurs, the factor of safety (FS) of slope varies as a function of transient pore pressure, depth and time. The landslide response process to rainfall is a time-varying process, which determines the landslide stability, landsliding depth, timing, style or scale.

Fig. 6 illustrates the slope stability response process at the whole range of depth of 4 different slopes discussed above. Fig. 7 demonstrates the stability response process over the whole rainfall process at certain depth (1, 2 and 3 m). By comparison analysis

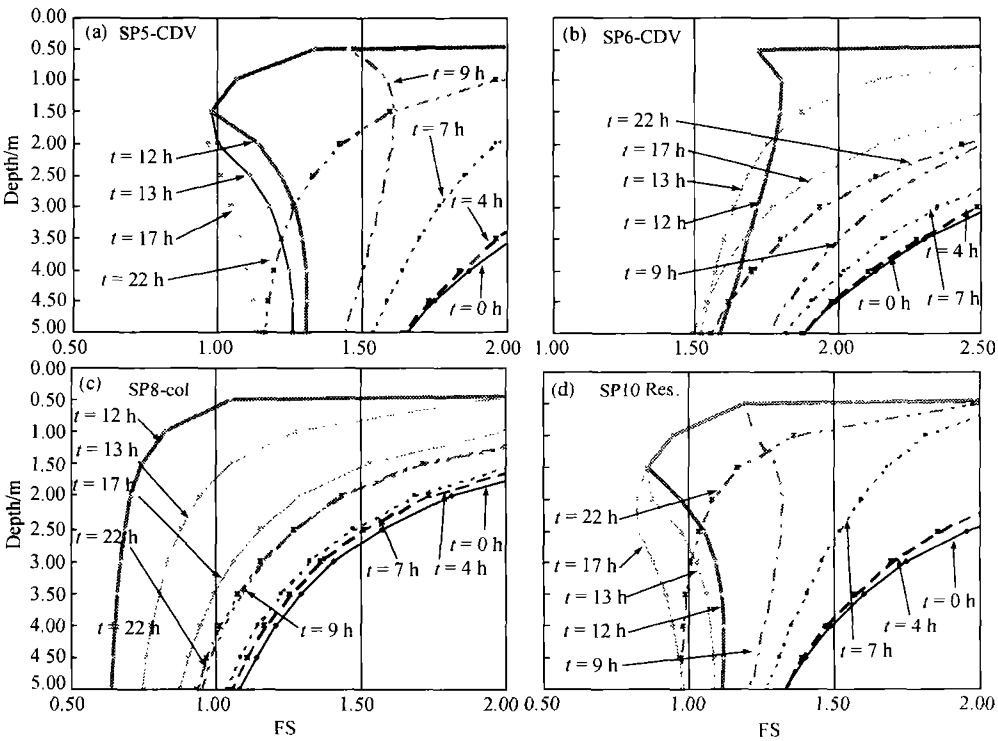

Fig. 6. Stability response at the range of depth in different slopes. (a) Low permeability SP5 in CDV; (b) high permeability SP6 in CDV; (c) high permeability SP8 in col; (d) low permeability SP10 in residual.

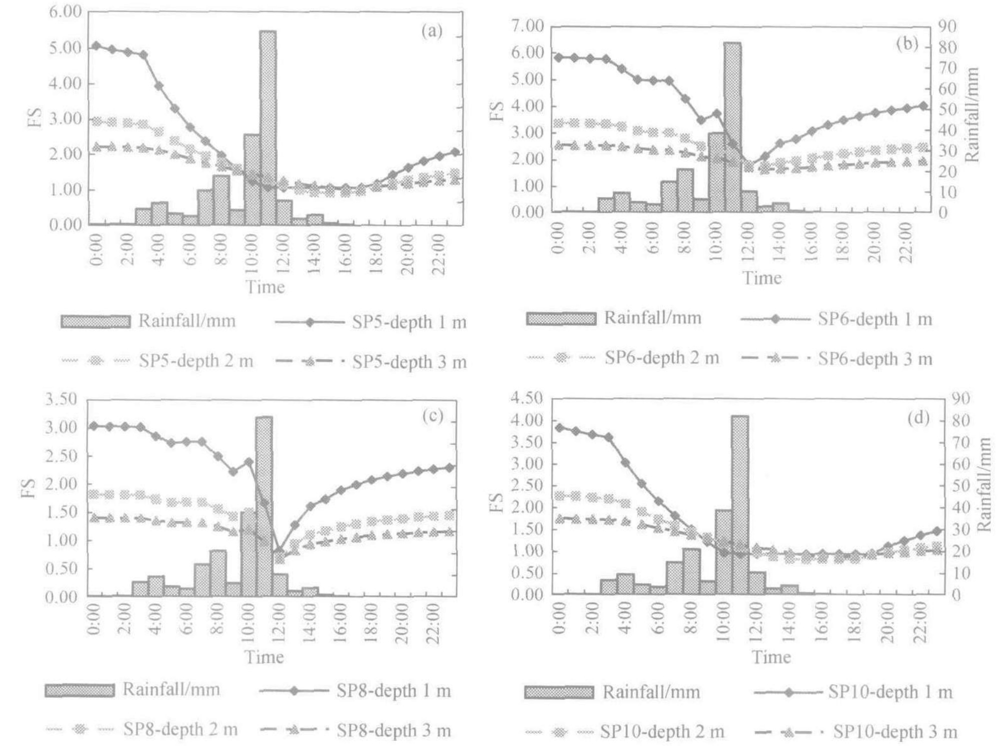

Fig. 7. Stability response process at 1, 2 and 3 m depth in different slopes. (a) Low permeability SP5 in CDV; (b) high permeability SP6 in CDV; (c) high permeability SP8 in col; (d) low permeability SP10 in residual.

between fig. 6 and fig. 7, we carried out a comprehensive study on the landslide stability response process to rainfall in low permeability and high permeability slopes.

4.1 Landslide stability response process in low permeability slope

In terms of the spreading feature of safety factor-depth curve, the slope SP5 and SP10 with low permeability has similar stability response characteristics to rainfall process which is controlled by similar pore pressure response (figs. 6(a) and (d), Figs. 7(a) and (d)). We use SP5 for detailed analysis of stability response process in low permeability slopes.

At the beginning period of rainfall (0—8 h), the whole slope remains stable according to the safety of factor. The rainfall intensity increases dramatically to 21 mm/h at t = 9 h and the different stability behaviors take place at shallow depth and greater depth. The factor of safety at shallow depth (<1.0 m) declines evidently owing to the rapid pore pressure response. But FS has almost no changes below the 1.00 m depth. The rainfall intensity of 20 mm/h can be considered as the index for initialing shallow slope failure at the weathered decomposed volcanic slopes. The decline of FS spreads downward during the rainfall process.

The FS at the range of depth remains larger than 1 until the period of peak rainfall

(t = 11 h). At one hour after peak rainfall (t = 12 h), the FS at 1.50 m depth declines to less than 1.0, indicating the potential slopes failure at this depth. This transient state of slope stability is also called critical stability state and does not assure that the slope failure will finally occur at this depth. Whether the slope failure will occur eventually at this depth is determined by the stability developing trend in response to rainfall and the stability state of rock and soil cells surrounding it. If the FS of this site declines gradually with time and so do the surrounding rock and soil cells, then the slope failure tends to occur with high probability. Therefore, the slope stability response is a function of time. The final stability cannot be predicted only by the stability response state at single point at certain period.

The depth of potential sliding plane (FS<1) increases gradually till the end of rainfall (t = 17 h). At t = 13 h, the potential sliding plane is about 2.0 m in depth, and up to 2.5 m at the end of rainfall process (t = 17 h). In this process, the minimum FS is located at 2.0 m depth. If landslide is triggered by this rainfall process, the depth of landsliding plane will be less than 2.5 m and larger than 1.0 m. And the most possible sliding plane is at 2.0 m in depth.

However, the state of FS less than 1 at the 1—2.5 m depth remains no longer enough for landsliding occurrence. Two hours after the cease of rainfall, the FS at whole range of depths develops rapidly up to larger than 1.0. The total period of critical stability state stays no longer than 5 h. According to the field investigation, there was no landsliding occurrence at SP5 triggered by this rainfall process. This indicates that the slope stability is also affected by the keeping time of critical stability state with FS less than 1. In this case, the critical stability state should remain longer than 5 h for the occurrence of landslide. The period of critical stability state for landsliding has close relationship to the pore pressure response and rainfall process characteristics. If the rainfall intensity is high and has longer duration, the high pore pressure response will keep a long time, and a shorter keeping time of critical stability state is required for landsliding. The landslide will occur at the same period of rainfall. This will explain the fact that the landslide occurrence is usually later than the rainfall process.

The slope stability response in residual SP10 has similar characteristics to that of SP5, except deeper potential sliding plane owing to the longer period of pore pressure response. According to field investigation, the occurrence of landslide in residual soil slope is common in the study area. Fig. 8 illustrates the process of pore pressure and stability response in SP10 to rainfall in August 1999 caused by typhoon Sam. It can be seen that this rainfall process resulted in a long term of high pore pressure head and a long term of critical stability state with FS<1. The slope failure occurred eventually at about 5 : 00 a.m., August 24, 1999. In addition, the residual soil is usually very thin and underlaid by layers with weak permeability, which leads to the high possibility of landsliding. In general, under the same rainfall condition, the slope failure in residual soil is more likely to occur than that in completely decomposed volcanic rocks and completely decomposed granitic rocks.

But under the rainfall process occurred on June 11, 2001, no obvious slope failure was observed in SP10. The possible reasons might be that (1) the keeping time of critical stability state with FS<1 was less than 5 h and it was not longer enough for landsliding and (2) the landsliding sources are short due to the cyclic slope evolution.

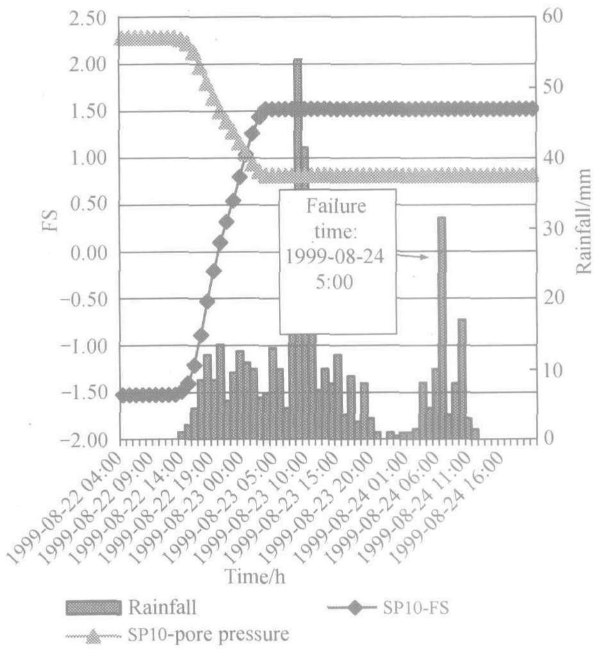

Fig. 8. Pore pressure and slope stability response in residual SP10 to rainfall in August 1999. The slope failure occurred eventually.

4.2 Landslide stability response process in high permeability slope

The stability response in slopes with high permeability (SP6 or SP8) shows much different characteristics to that of lower permeability slopes (figs. 6(b) and 6(c), Figs. 7(b) and (c)). Because of the high hydraulic conductivity and diffusivity, the stability at different depths tends to response simultaneously to rainfall process, especially at the beginning period of rainfall with low rainfall intensity. In contrast, the factor of safety at shallow slope with low permeability shows rapid changes at the beginning period of rainfall. If the rainfall increases to some extent, the FS in shallow slope with high permeability will decline dramatically. If the rainfall intensity keeps rising, the rapid shallow or slump will occur. Under the condition of longer rainfall duration, the high stability response tends to occur at greater depth, which may lead to deep seated landslide. Comparing the curve at t = 12 h and t = 13 h, it can be seen that the slope above 2 m depth tends to be stable, but the FS below 2 m depth tends to decline, indicating that the slope with high permeability has a tendency of failure at greater depth.

The slope stability in SP8 in colluviums with most high permeability has a tendency for rapid response at whole range depth to rainfall under a most intense rainfall process. The critical stability state will be rapidly reached. However, the stable state will develop rapidly at the end period of rainfall process. Underlaid by weak permeability layers, the effect of transient pore pressure tends to affect slope stability for a long period and the colluviums slope has a tendency to lose its stability under the appropriate geomorphological and geological conditions.

4.3 Discussion

To summarize, in the lower permeability slope (such as SP5 in decomposed volcanics or SP10 in residual soil), the infiltration capacity of slope will be quickly reached, leading to the rapid loss of soil suction at the shallow depths at relatively modest rainfall. Therefore, the shallow slope with lower permeability has rapid slope stability response and the deep slope has slow stability response (fig. 7(a) and (d)). The FS at shallow depth (such at 1 m depth) declines rapidly to less than 1.0 owing to the peak rainfall and this low FS value tends to remain a long time during the rainfall process, indicating that the slope with lower permeability might be most prone to shallow failures of this nature. The stability response at greater depth will be limited and will take longer time to occur. At the end period of rainfall process with decreasing rainfall intensity. the soil suction will develop slowly and there might be tendency for continuous pore pressure effect on the slope stability at shallow depth. Some slope failure might occur at this period.

In contrast, in slope with high permeability (such as SP8 in colluviums and SP6 in decomposed volcanics with more relic joints), it takes more intense rainfall to exceed the infiltration capacity. Runoff will be lower. At the beginning period of rainfall with low rainfall intensity, slope stability in response to rainfall tends to remain stable at the whole range of depth. Loss of suction will be less for lower permeability slope under the same conditions. Under the period of more intense rainfall (such as 82 mm/h in this case), the FS in shallow depth tends to decline rapidly and spread downward to greater depth. If the long rainfall duration with high rainfall intensity is satisfied, slope failure will occur to greater depths. During the end period of rainfall with lower rainfall intensity, the soil suction will develop more rapidly than that of lower permeability slope.

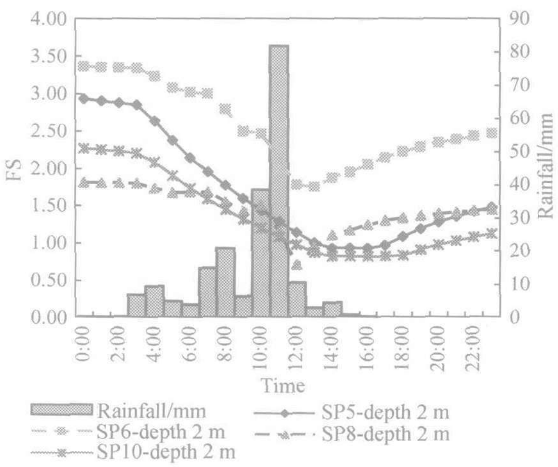

Fig. 9. Comparison analysis of slope stability response process at 2 m depth in different slopes.

Comparison analysis of stability response between different slopes at the same 2 m depth can further confirm the conclusions discussed as above (fig. 9).

5 Concluding remarks

Some conclusions can be drawn by the rainfall-induced landslide stability analysis in response to transient pore pressure.

(i) Shallow landslide is mainly triggered by transient pore pressure in response to short intense rainfall process.

(ii) Antecedent rainfall and landslide stability: Antecedent rainfall might affect landslide stability by losing soil suction (negative pore pressure), increasing positive transient pore pressure and then accelerating the stability response. The effect of antecedent rainfall on landslide stability has close relationship to the slope permeability and slope depth. Antecedent rainfall has slight effect on the slope stability in Hong Kong owing to its high permeability.

(iii) Pore pressure response time and landslide stability: Pore pressure response time to rainfall process is a function of rainfall intensity, time, slope permeability and slope depth, which can be used for landslide warning.

(iv) Landslide stability in response to transient pore pressure: The tempo-spatial characteristics of landslide stability (including location, timing, rate, style or scale) are primarily dominated by pore pressure response to short intense rainfall.

Slope stability with different hydraulic properties (such as permeability) demonstrates much different behaviors in response to rainfall process. Slopes with lower permeability are most prone to shallow failure owing to the remarkable pore pressure response to rainfall process, which leads to the remarkable loss of soil suction or rise of positive pore pressure under moderately intense rainfall or even at the end period of rainfall process. In contrast, under the same rainfall condition, the slopes with high permeability tend to remain stable owing to the slight pore pressure response to rainfall at the whole range of depth. They need more intensive rainfall and longer duration for landsliding and have a tendency to occur at greater depth. This might be useful to understand the fact that landslips in weathered volcanic rocks are more serious that that in weathered granitic rocks in Lantau Island, Hong Kong.

(v) To predict the final slope failure, the keeping time of critical slope stability state (FS =1 or slightly less than 1) should be taken into account. The required keeping time is mainly determined by characteristics of transient pore pressure response process to rainfall. With longer keeping time of critical slope stability state, the landsliding plane has more tendency to form and the final slope failure will be likely to occur.

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