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Numerical Modelling of Rainfall Influence on the Susceptibility of a Slope to Sliding under Induced Compression

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Abstract: This study examines the pore water pressure responses and stability of an unsaturated–saturated consolidating slope under the influence of rainfall infiltration. Analysis of slope behaviour was carried out with the results obtained for soils having similar saturated coefficients of permeability (k_s) of 1×10^{-5} m/s, and rainfall flux (q) of 1×10^{-6} m/s but varying air-entry and coefficient of volumetric compression (mv) values. Results indicate that for the unsaturated portion of the slope (above the groundwater table), negative pore water pressure exists during rainfall infiltration which tends to lessen as the duration of rainfall progresses. An increase in soil compressibility caused a decrease in soil suction in the unsaturated portion irrespective of the rising groundwater level during infiltration. The difference in the pore water distribution was less for mv values below 0.002 kPa^{-1} especially under major rainfall events. The stability of the slope reduced with an increment in infiltration time as soil compression increased, with the difference being slightly more pronounced under antecedent rainfall of duration greater than 7 days. Although the studied slope appeared to be just safe (factor of safety of 1.2) under the conditions of increased air-entry value, increased compression, and rainfall flux of 1×10^{-6} m/s, the stability of the slope was observed to have been compromised when the rainfall flux was equal to or greater than the saturated coefficient of permeability (1×10^{-5} m/s) of the soil.

Keywords: rainfall; soil compression; slope stability; pore water pressure; soil suction; factor of safety

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1. Introduction

Climate change is predicted to trigger more fluctuations in the patterns of rainfall in the long term [1]. The alterations in the frequency, intensity, and amount of precipitation can result in the deformation of soil slopes leading to instability. Slope failures and general landslides are responsible for thousands of fatalities and millions of dollars' worth of damage to critical infrastructural assets such as railways, roadways, and flood defence systems [2]. In geotechnical engineering, the effects of infiltration and seepage on the stability of soil slopes are normally addressed through the determination of the factor of safety or in some instances, critical depth [3]. This type of analysis lends itself to saturated steady-state flow occurring over a given depth. To account for the worst-case scenario of rainfall infiltration, it is usually presumed that the groundwater table (or the phreatic surface) would gradually rise to coincide with the surface of the slope, hence rendering a completely saturated condition [4]. In a fully saturated slope, additional seepage or infiltration may not be feasible, hence, precipitation will have no further effect on the stability of the slope. However, it has been proven through in situ measurements of matric suction that negative pore water pressures in a soil slope may not be entirely destroyed following a rainstorm [3,5]. In this regard, it is possible for some amount of shear strength to be sustained in such slope conditions.

Previous studies have demonstrated that the hydraulic responses of a slope to precipitation can be broadly divided into two major stages, namely: (1) the propagation of a wetting front and (2) the rise of groundwater table [4,6,7]. Based on the theory of infiltration and seepage through an unsaturated–saturated soil system, certain conditions under which soil suction can be maintained in a slope with an advancing wetting front resulting from rainfall has been established in the past [8–10]. Under steady state conditions, one of the most important factors that can contribute to the permanency or maintenance of matric suction in soil slopes is the amount of precipitation experienced by the soil. This magnitude of precipitation (or rainfall flux) can also be expressed as a ratio or percentage of the saturated coefficient of permeability of the soil [11]. For soils with low saturated coefficient of permeability (or larger water storage capacity), the negative pore water pressure may require a sufficient amount of time to dissipate in order to ensure that it is maintained over a longer time duration than the rain is likely to last, even if the rainfall intensity (or ground surface flux) is greater than or equal to the saturated coefficient of permeability [12,13].

Previous studies have also shown that under transient conditions of seepage, pore water pressure is dependent on the magnitude of rainfall, saturated coefficient of permeability, desaturation coefficient, slope geometry, and unsaturated soil property functions such as the air-entry value of the soil and the water storage function [5,14–18]. Although not explicitly considered in most previous research in the recent past, it is proposed that slope stability analysis should also incorporate the behaviour of pore water pressure of a slope that is subjected to consolidation from external forces (or under its own self weight) during a rainfall event.

Hence, the present study aims to examine and evaluate, through an unsaturated –saturated infiltration and seepage model, the matric suction response and the stability of a consolidating slope subjected to rainfall. The conditions leading to the maintenance of negative pore water pressure in the unsaturated zone of the slope are studied under transient-seepage conditions using finite element numerical modelling. Furthermore, semi-parametric analysis is carried out to include a range of unsaturated soil and volume conditions with an investigation of the stability of the slope under those conditions.

2. Theory of Infiltration and Seepage in Unsaturated–Saturated Soils

Darcy's law governs water flow in unsaturated and saturated soils [19]. According to Darcy's law, the velocity of discharge is proportional to the gradient of hydraulic head:

$$v = -k\,\frac{\delta h}{\delta y} \tag{1}$$

where k is the coefficient of permeability, h is the hydraulic head, and $\delta h/\delta y$ is the hydraulic gradient in the y direction.

The hydraulic head h is composed of an elevation head y and a pore water pressure head as follows:

$$h = y + \frac{u_w}{\rho_w g} \tag{2}$$

where u_w is the pore water pressure, ρ_w is the density of water, and g is the acceleration due to gravity. For a saturated soil, the coefficient of permeability can be considered as a constant value. However, for unsaturated soils, the coefficient of permeability is normally regarded as a function of negative pore water pressure (matric suction) and tends to decrease with increasing suction.

The relationship between matric suction and the coefficient of permeability for an unsaturated soil is referred to as the permeability function. Darcy's law and the equation of continuity, the governing equation for two-dimensional transient flow through an unsaturated soil, can be expressed as:

$$\frac{\delta}{\delta x}\left(k_x\frac{\delta h}{\delta x}\right) + \frac{\delta}{\delta y}\left(k_y\frac{\delta h}{\delta x}\right) = \frac{\delta \theta_w}{\delta t} \tag{3}$$

where k_x is the coefficient of permeability in the x direction, k_y is the coefficient of permeability in the y direction, and θ_w is the volumetric or gravimetric water content.

The water phase constitutive relationship proposed by Fredlund and Morgenstern [20] for an unsaturated soil can be expressed as follows:

$$d\theta_w = m_1^w d(\sigma - u_a) + m_2^w d(u_a - u_w) \tag{4}$$

where σ is the total stress; u_a is the pore air pressure; ${m_1}^w$ is the slope of the water volume vs. $\sigma - u_a$ relationship when $d\ (u_a - u_w)$ is equal to zero; ${m_2}^w$ is the water storage coefficient representing the slope of the water volume vs. $(u_a - u_w)$ relationship when $(u_a - u_w)$ is equal to zero.

For an analysis involving transient seepage, it can be assumed that the pore air pressure remains at atmospheric conditions while the total stress is constant. Then, a change in porewater pressure can be related to volumetric water content as follows:

$$d\theta_w = m_2^w d(u_a - u_w) \tag{5}$$

Substituting Equations (2) and (5) into Equation (3) yields the following governing equation for water flow through an unsaturated soil:

$$\frac{\delta}{\delta x}\left(k_x \frac{\delta h}{\delta x}\right) + \frac{\delta}{\delta y}\left(k_y \frac{\delta h}{\delta x}\right) = m_2^w \rho_w g \frac{\delta h}{\delta t} \tag{6}$$

3. Methodology

3.1. Slope Properties and Design

This study models transient seepage conditions on a simplified slope of height 20 m inclined at an angle of 30 degrees. In keeping with the primary aim of this research, the slope is initially composed of an isotopic and homogeneous soil having a unit weight of 20 kN/m^3, cohesion of 15 kPa, and an angle of friction of 30 degrees. The analysis and design of the slope is based on Eurocode 7, Design Approach 1, Combination 2 using the Mohr–Coulomb strength type. As would be described in the section following, the slope presupposes the existence of an unsaturated region above the groundwater table during infiltration. Hence, unsaturated soil properties using the [21] soil–water characteristic curve (SWCC) model with varying a_f values (0.1, 0.5, 1, 2, 5, 10, and 20 kPa) and constant n_f and m_f values of 2 and 1, respectively, are adopted. The a_f value relates to the air-entry value of the soils, the n_f value is a fitting parameter and represents an SWCC's slope function, while m_f is a fitting parameter of the SWCC, being a function of the residual water content. The saturated coefficient of permeability (k_s) value of 1×10^{-5} m/s is used in this study. The SWCC and the corresponding coefficient of permeability functions for the soils with various a_f values adopting the [21] model are shown in Figure 1a,b.

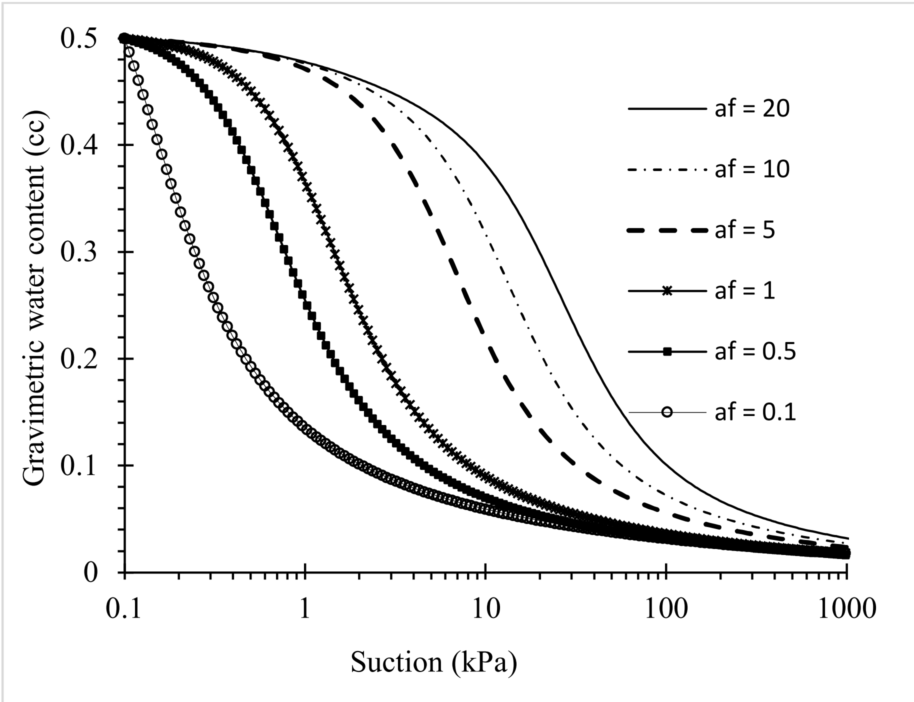
3.2. Numerical Modelling and Boundary Conditions

Finite element modelling of groundwater considering transient seepage was conducted on the slope. The finite element mesh and corresponding boundary conditions adopted for the slope following the model proposed by Zhang L. [3] is shown in Figure 2. Along the left- and right-side boundaries of the slope, a variable head was applied at elevation 60 m and 50 m, respectively, at the groundwater table. This study considers a free water table condition since this may rise during rainfall infiltration. It is assumed that the base of the finite element mesh applied on the slope is impermeable. The mesh element type used is four-noded quadrilaterals; the total number of elements and nodes are 3366 and 3432, respectively. Numerical simulation is executed using the Slide2 program [22].

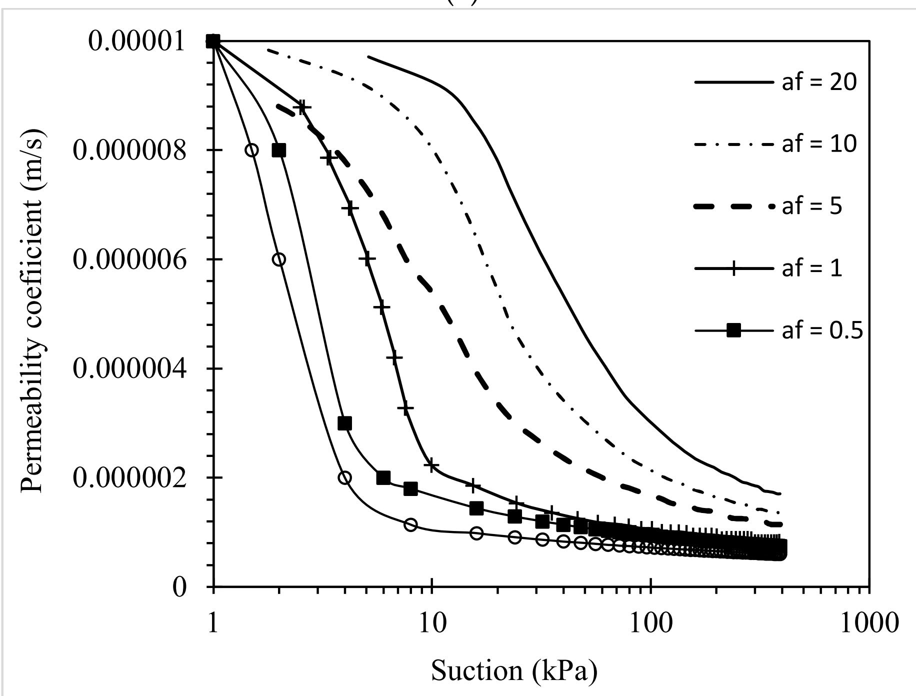
High rainfall intensities can lead to rapid infiltration of water into the slope, especially if the soil's air-entry value (AEV) is low. This rapid infiltration increases pore water pressures swiftly, reducing the soil's effective stress and shear strength.

Continuous high-intensity rainfall can saturate the slope, making it more prone to shallow failures or surface erosion.

On the other hand, lower rainfall intensities might allow for better drainage and dissipation of pore water pressures, reducing the immediate threat to slope stability.



(**a**)



(**b**)

Figure 1. (**a**) Soil–water characteristic curve for different air-entry values. (**b**) Coefficient of permeability curve for different air-entry values.

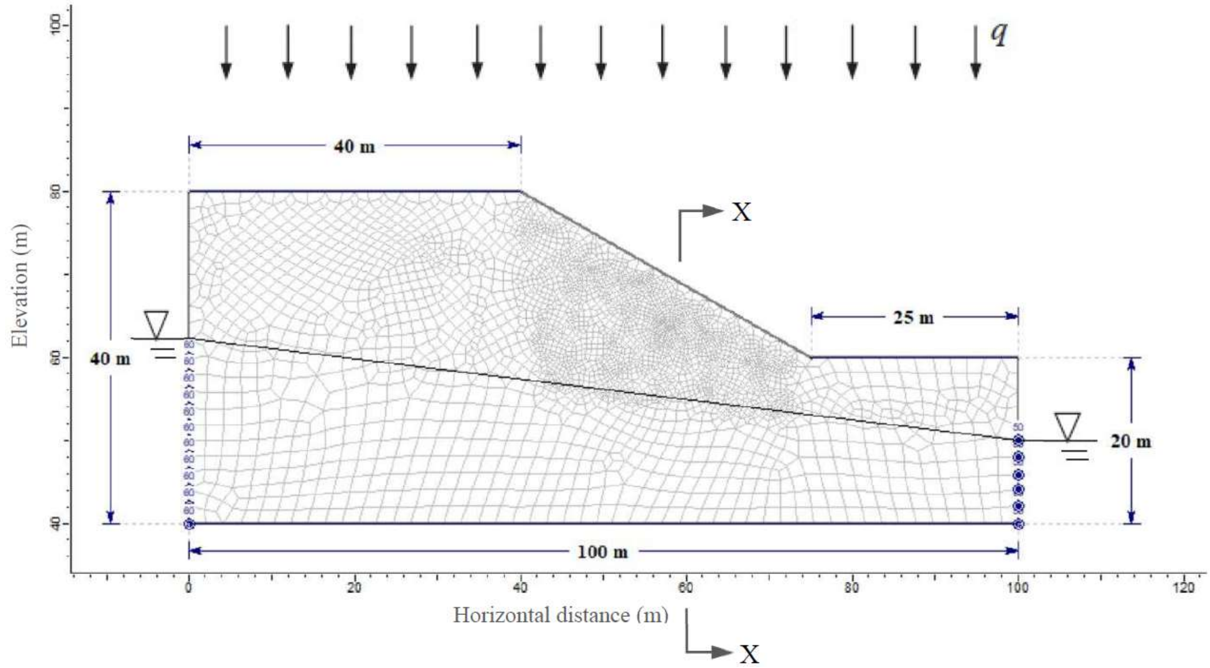


Figure 2. Slope geometry with finite element mesh and boundary conditions.

In this study, rainfall effect is modelled as a flux boundary (q), applied along the surface of the slope. Analysis of unsaturated suction and pore water profiles are carried out in the middle of the slope at the section denoted as X-X in Figure 2; for an unsaturated soil condition above the groundwater table, suction could be sustained if the rainfall intensity or surface flux (q) is less than the saturated coefficient of permeability (k_s) [3]. In this regard, the ratio of surface flux to the saturated coefficient of permeability (i.e., q/k_s) less than unity ensures the slope is not fully saturated during infiltration. A typical pore pressure distribution profile with increasing q/k_s is shown in Figure 3. Hence, a rainfall intensity value of 1×10^{-6} m/s (i.e., q/k_s of 0.1) has been adopted for this study. Critical porewater profiles are analysed in this study considering both major and antecedent rainfalls. A major rainfall event is that which has a duration of less than 24 h while an antecedent rainfall is considered as that which would last for more than 24 h [23].

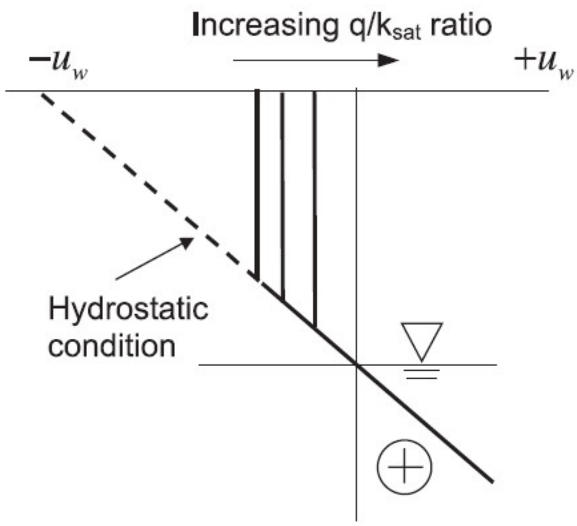


Figure 3. Typical pore water pressure distribution profiles in an unsaturated soil with increasing surface flux.

4. Analysis and Discussion

4.1. Effect of Air Entry on Porewater Condition

The results shown plotted in Figure 4 illustrate the different patterns realised throughout the pore water pressure distribution profile with the value of "a_f" equal to 0.1, 0.5, 1, 5, 10, and 20 kPa, respectively. These results were obtained for soils having similar saturated coefficients of permeability (k_s) of 1×10^{-5} m/s, n_f of 2, and m_f of 1. Rainfall flux (q) of 1×10^{-6} m/s (i.e., q/k_s of 0.1) was applied on the slope.

Mechanism by Which Air Entry Affects Slope Stability

The air-entry value (AEV) is a measure of the matric suction head at which air starts to enter the soil's pores, leading to a rapid drop in the soil's water retention capacity. It is a key parameter in the soil–water characteristic curve.

Soils with higher AEVs tend to resist water infiltration for longer durations during rainfall events. This resistance means that the buildup of pore water pressures, which can reduce the soil's shear strength, is delayed.

Conversely, a lower AEV implies that the soil becomes saturated more quickly, leading to a faster rise in pore water pressures, which can compromise slope stability.

For the soil with a_f that is equal to 0.1 kPa, the negative pore pressure (or matric suction) near the ground surface is seen to decrease with time (Figure 4). There is a clear distinction between the curves which indicate progressive movement, suggesting a rise in the groundwater as the infiltration continues. It is also observed that although there are relatively different values of suction for infiltration occurring from 1 min up to 24 h (1 day) of rainfall above the water table, the level of groundwater rise seems not to change. However, the reverse seems to be the case as infiltration continues up until 7 days beyond which the suction seems to remain the same even though the level of groundwater rise is greater with the passage of time. Groundwater rises by about 1 m between the major rainfall conditions (1 min–24 h) and 7 days and by 4 m between the major rainfall conditions and 30 days.

At greater values of a_f (also indicating higher air-entry value), the suction of the soil during rainfall infiltration above the groundwater table generally seems to increase, as could be observed from Figure 4. Also, a distinct "vertical" wetting front with a slightly sharp separation of pore water profiles of the antecedent rainfall from the major rainfall conditions is noticed with a reduction in the air-entry values of the soil. However, as the a_f value increases, the wetting front becomes less distinct, but with the gradient of the pore water pressure being greater for the soil with smaller air entry.

As rainfall infiltration progresses, the level of groundwater rise seems to be almost equal at about 2 m for a_f values between 5 kPa and 10 kPa. However, there seems to be a slight distinction in the progress of infiltration and water levels at the a_f value of 20 kPa. In this regard, there is a small increase in the water level between 1 min of rainfall and that lasting for 1 day or 24 h. It is also observed from Figure 5 that the level of rise in the groundwater across the infiltration times are generally lower for higher air-entry values of the soil.

Figure 6 shows more clearly the pore water pressure profile highlighting the differences in the matric suction for different air-entry values as the time of infiltration increases when re-cast with varying durations. It is obvious that higher matric suctions are accorded to the soils having higher air entry across all infiltration durations. However, as the time of rainfall progresses, the matric suction values tend to reduce with increasing a_f value.

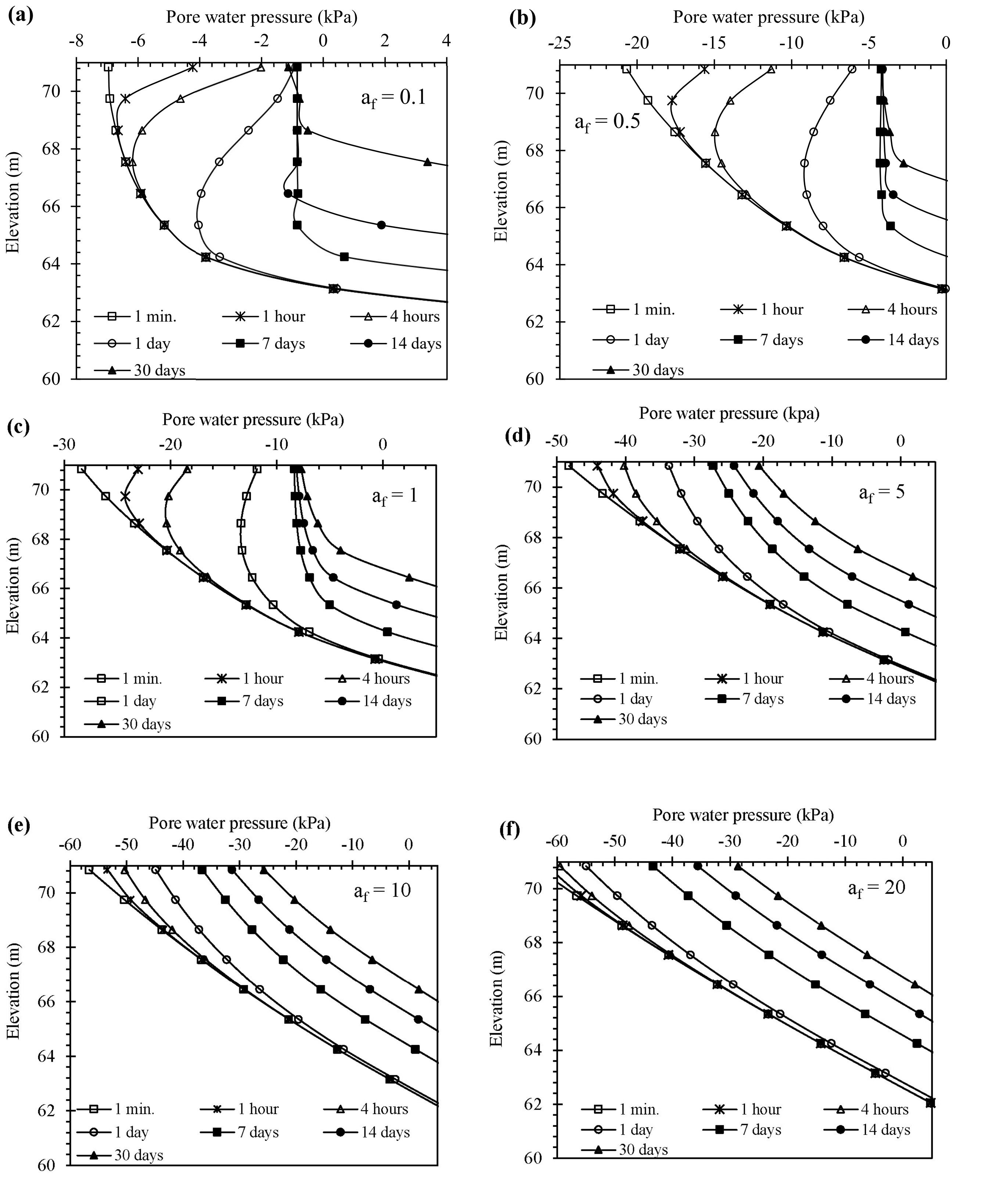
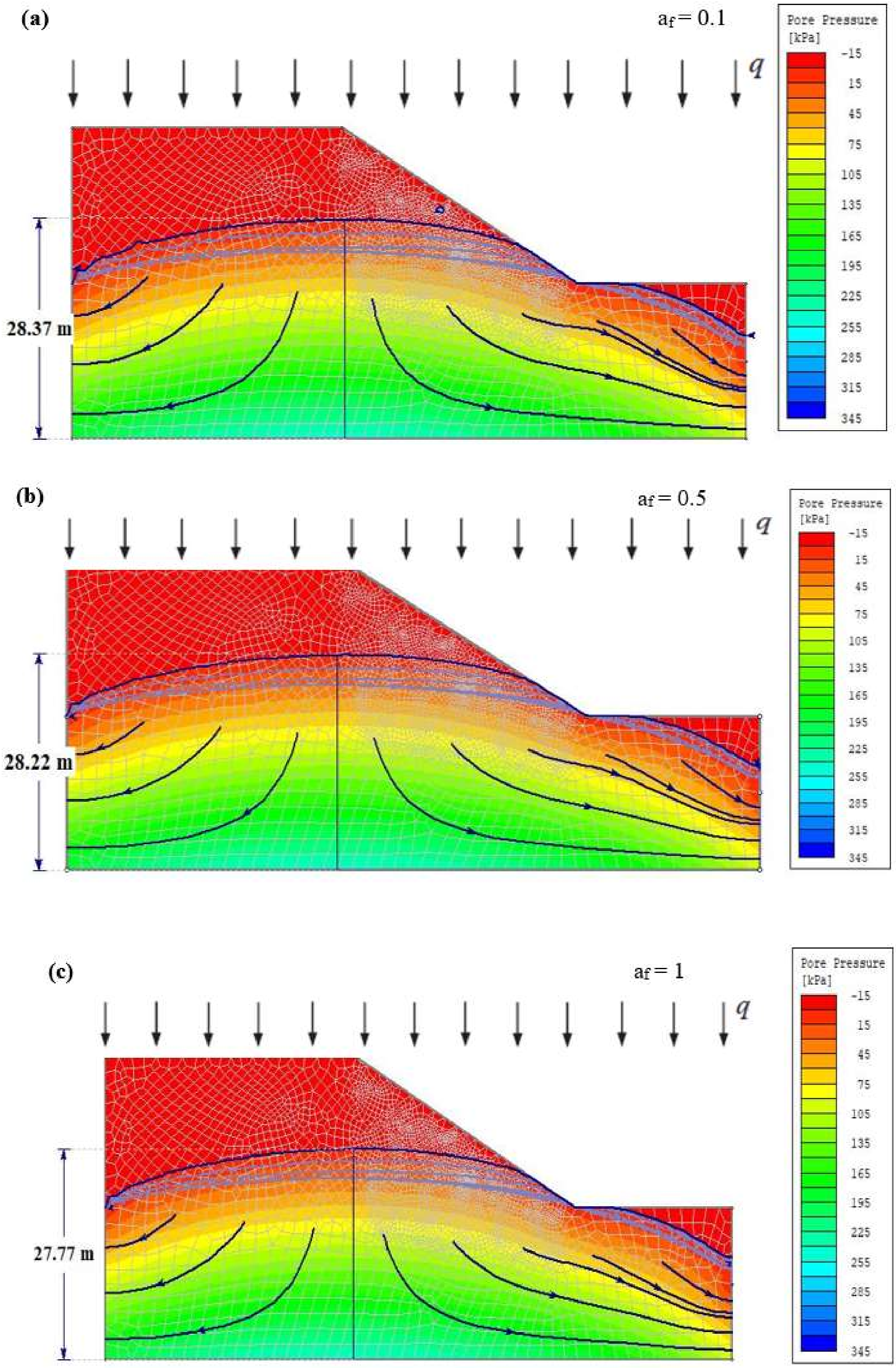


Figure 4. Pore water pressure distribution and duration of rainfall. (**a**) Pore water pressure profile with a_f = 0.1; (**b**) pore water pressure profile with a_f = 0.5; (**c**) pore water pressure profile with a_f = 1; (**d**) pore water pressure profile with a_f = 5; (**e**) pore water pressure profile with a_f = 10; (**f**) pore water pressure profile with a_f = 20.



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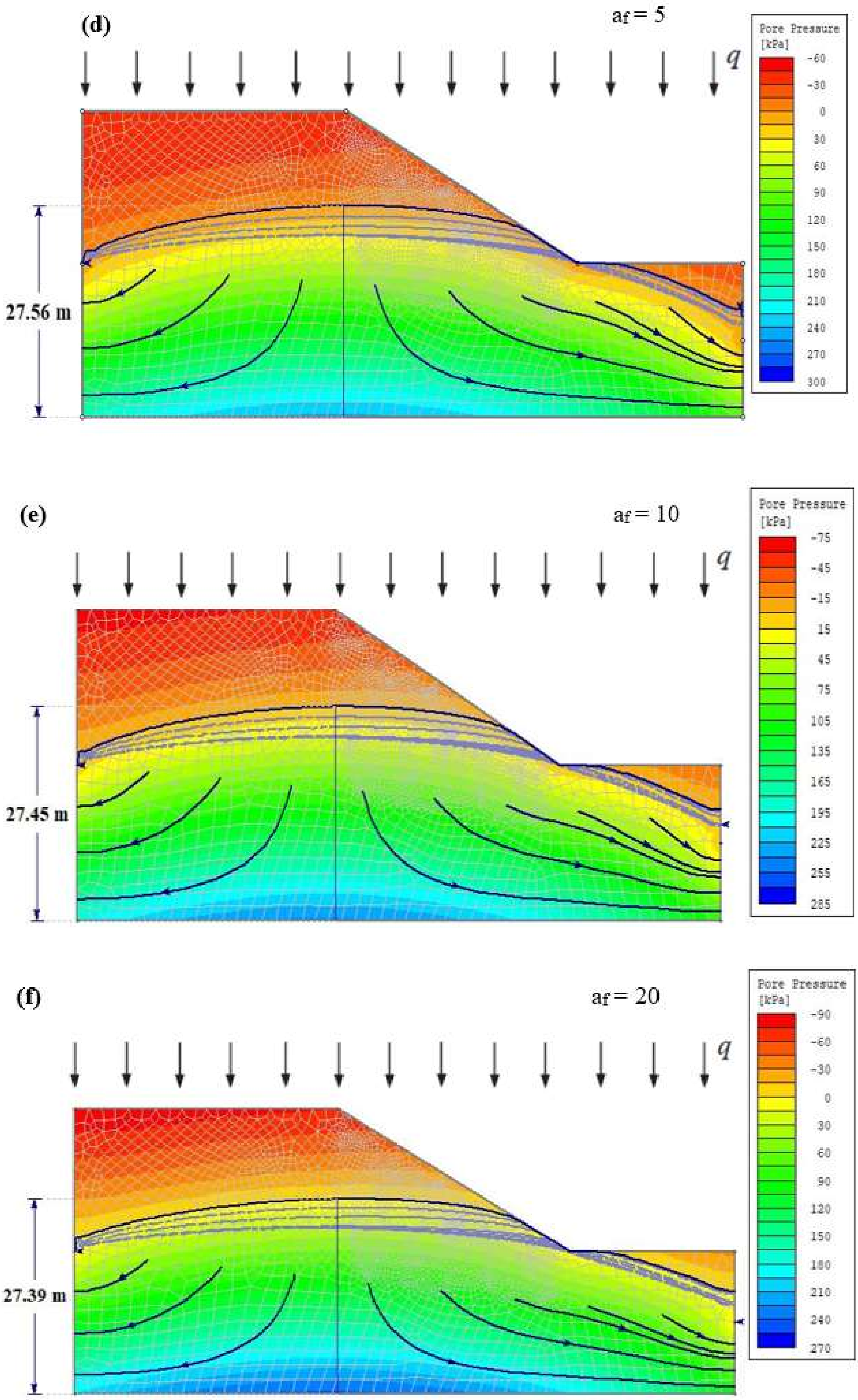


Figure 5. Rainfall flux and groundwater profiles where (**a**) a_f = 0.1, (**b**) a_f = 0.5, (**c**) a_f = 1, (**d**) a_f = 5, (**e**) a_f = 10, (**f**) a_f = 20.

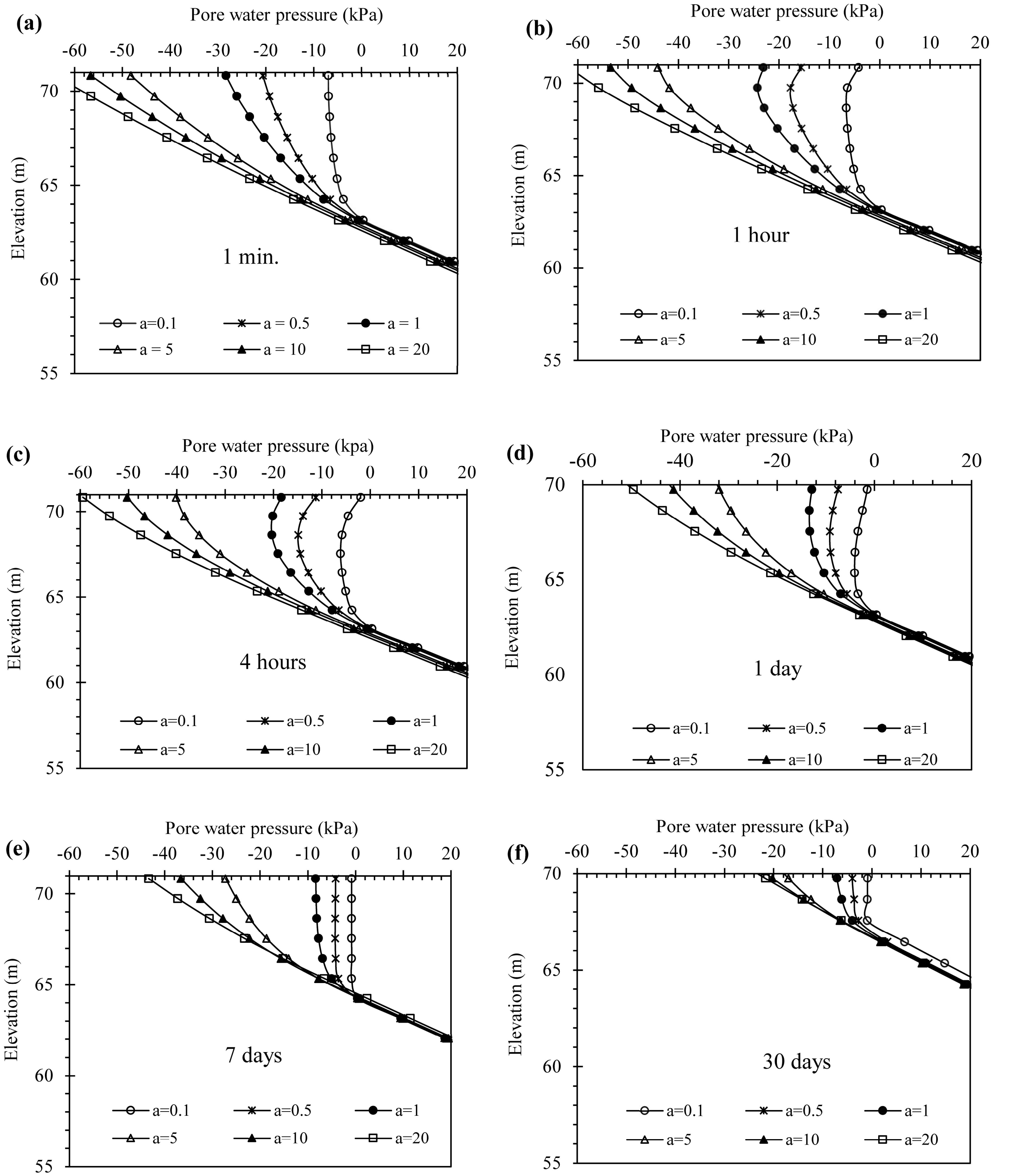


Figure 6. Pore water pressure for different rainfall durations and a_f values with (**a**) 1 min duration, (**b**) 1 h duration, (**c**) 4 h duration, (**d**) 1 day duration, (**e**) 7 days duration, (**f**) 30 days duration.

4.2. Effect of Soil Consolidation on Porewater Condition

The effect of volume change either from external loading or self-weight of soil is modelled using the coefficient of volume change (mv), often regarded as the volumetric change in a soil per unit increase in effective stress.

Mechanism by Which Coefficient of Volumetric Compression Affects Slope Stability

When water infiltrates a slope, the resulting increase in pore water pressures leads to a decrease in the soil's effective stress. Soil with a higher m_v will undergo a more significant volume reduction (or compression) for a given increase in pore water pressure.

This compression can lead to a decrease in the soil's shear strength, making the slope more susceptible to failure, especially in fine-grained soils.

The results in Figure 7 were obtained for soils having similar q/k_s of 0.1, a_f of 0.5 kPa, n_f of 2, and mf of 1. The pore water pressure distribution profiles shown correspond to soils with an mv of 0.2, 0.02, 0.002, 0.0002, 0.00002, and 0.000002 (kPa^{-1}) which invariably represent a broad range of pressure that could be experienced by the slope. For an mv of 0.2 kPa^{-1}, the pore water pressure profile is very similar for infiltration occurring under 1 day of major rainfall. However, with decreasing mv, the distinction in the profiles seems clear for infiltration occurring under major rainfall (i.e., between 1 h up to 24 h/1 day) and antecedent rainfall afterwards. Beyond 1 day, the suction in the unsaturated zone tends to approach zero for antecedent rainfall experienced by the slope up to 30 days. The pore water pressure profiles all tend to converge to the initial antecedent rainfall stages at suction values of about 10 kPa. Generally, it is noticed that an increase in soil compressibility does tend to result in a decrease in soil suction above the rising groundwater level although the difference in the pore water profiles seems less for mv values below 0.002 kPa^{-1}. Also, similar to an earlier behaviour with the effect of air entry considered, a distinct "vertical" wetting front with a slightly sharp separation of pore water pressure profiles of the antecedent rainfall from the major rainfall conditions can be observed for mv values of 0.002 kPa^{-1} and lower. Moreover, for mv values lower than 0.2 kPa^{-1} (i.e., increased soil compressibility), the rise in groundwater level is clearly noticeable for antecedent rainfall or infiltration occurring beyond days (please see Figure 8). Although the mv for a soil is not an intrinsic property but depends on the stress range from which it is calculated, it is clear that a reduction in the volumetric compressibility of a soil due to stress change results in the reduction in soil suction in the unsaturated zone during rainfall infiltration, irrespective of whether the advancing groundwater level for rainfall is less than the saturated permeability of the soil. Increased soil compression means a gradual reduction in volume; therefore, the interaction between the re-arranged soil particles and the infiltrated rainwater (which does merit further investigation at a microscopic level) tends to lead to less suction with prolonged rainfall. It should be borne in mind that reduced soil volume incontrovertibly results in a decrease in pore spaces in the soil which, in an unsaturated soil, would mean increased suction. However, as this study suggests, although some antecedent rainfall may cause the suction to be eventually wiped out, for the period within which suction can still be maintained in the unsaturated zone, further investigations are required at the microscopic level to enable an understanding of the phenomenon of pore arrangements during volumetric changes under rainfall. As seen in Figure 7, there seems to be only little difference in the pore water profiles for mv values 0.02 kPa^{-1}. Most test standards would often specify a single value of mv, determined for a stress increase of 100 kPa in excess of the in situ vertical effective stress of the soil at the depth being sampled (i.e., effective overburden pressure) [24]. Hence, it could therefore be established that for most geotechnical applications, mv values can be specified or calculated within the range between 100 kPa and 1000 kPa.

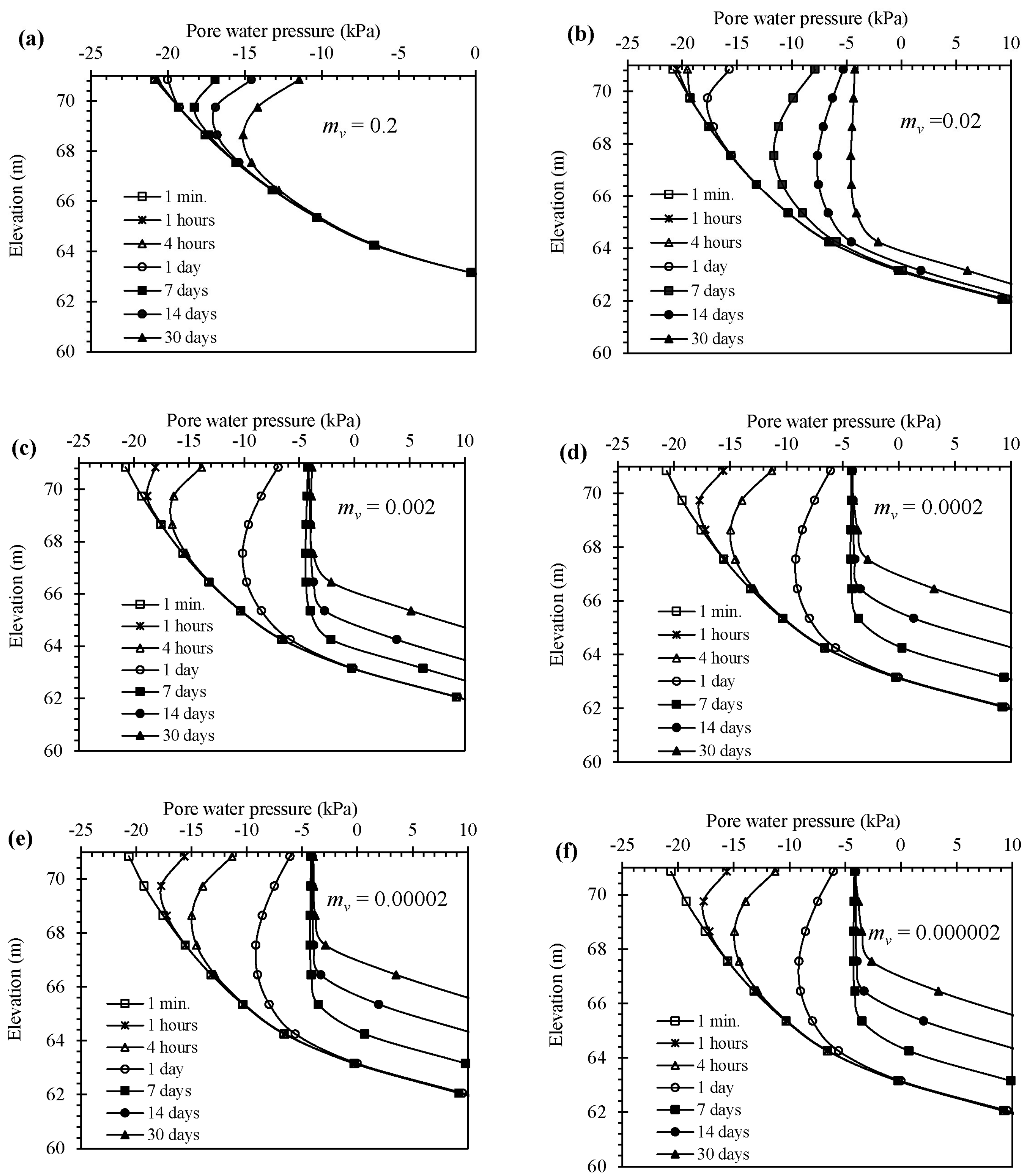
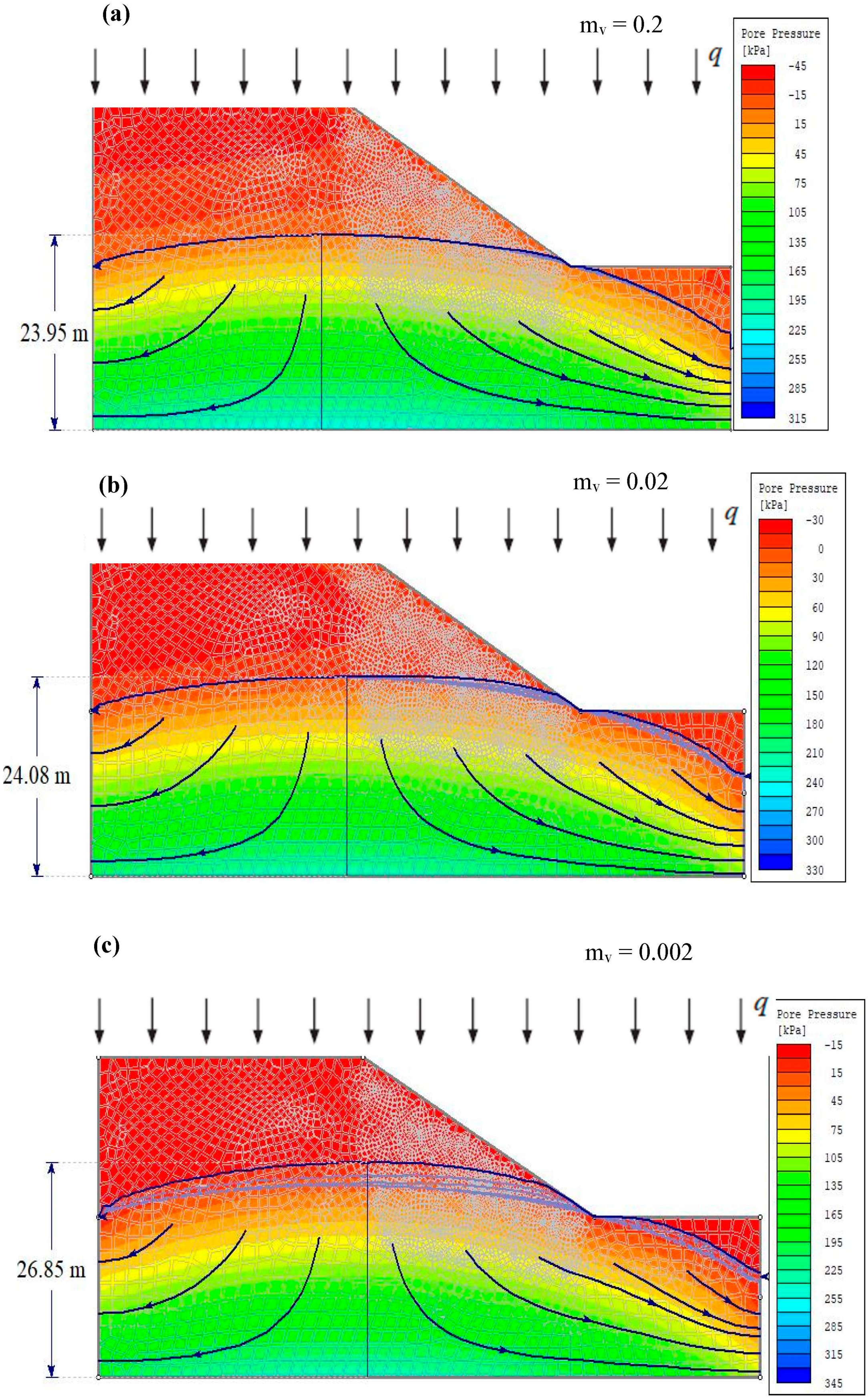


Figure 7. Pore water pressure distribution and duration of rainfall. (**a**) Pore water pressure profile with m_v = 0.2. (**b**) Pore water pressure profile with m_v = 0.02. (**c**) Pore water pressure profile with m_v = 0.002. (**d**) Pore water pressure profile with m_v = 0.0002. (**e**) Pore water pressure profile with m_v = 0.00002. (**f**) Pore water pressure profile with m_v = 0.000002.



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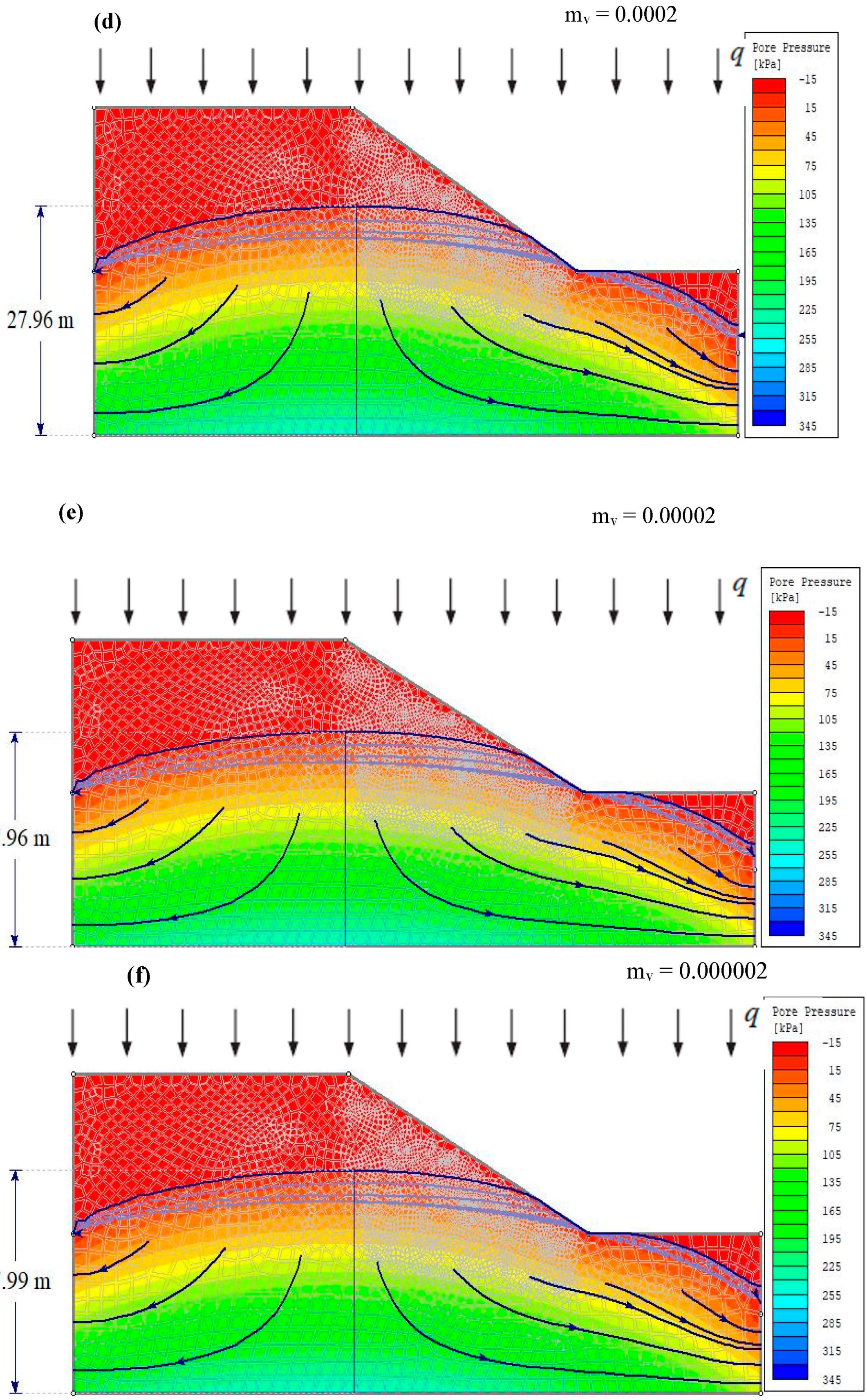


Figure 8. Rainfall flux and groundwater profiles where (**a**) m_v = 0.2, (**b**) m_v = 0.02, (**c**) m_v = 0.002, (**d**) m_v = 0.0002, (**e**) m_v = 0.00002, (**f**) m_v = 0.000002.

Figure 9 shows distinctly the pore water pressure distribution profiles of the slope with different values of mv but with the duration of infiltration considered separately. Suction values of up to 20 kPa are generally observed in the unsaturated zone with precipitation intensity of 1×10^{-6} m/s (or q/k_s = 0.1). There is no difference in the behaviour of the soil in the unsaturated zone for a major rainfall of 1 min duration. The distribution of the soil suction profile seems marginal for infiltration durations of 1 h to 4 h. The difference in soil suction seems to be more for mv less than 0.02 kPa^{-1}. This distinction seems to be greater with prolonged antecedent rainfall.

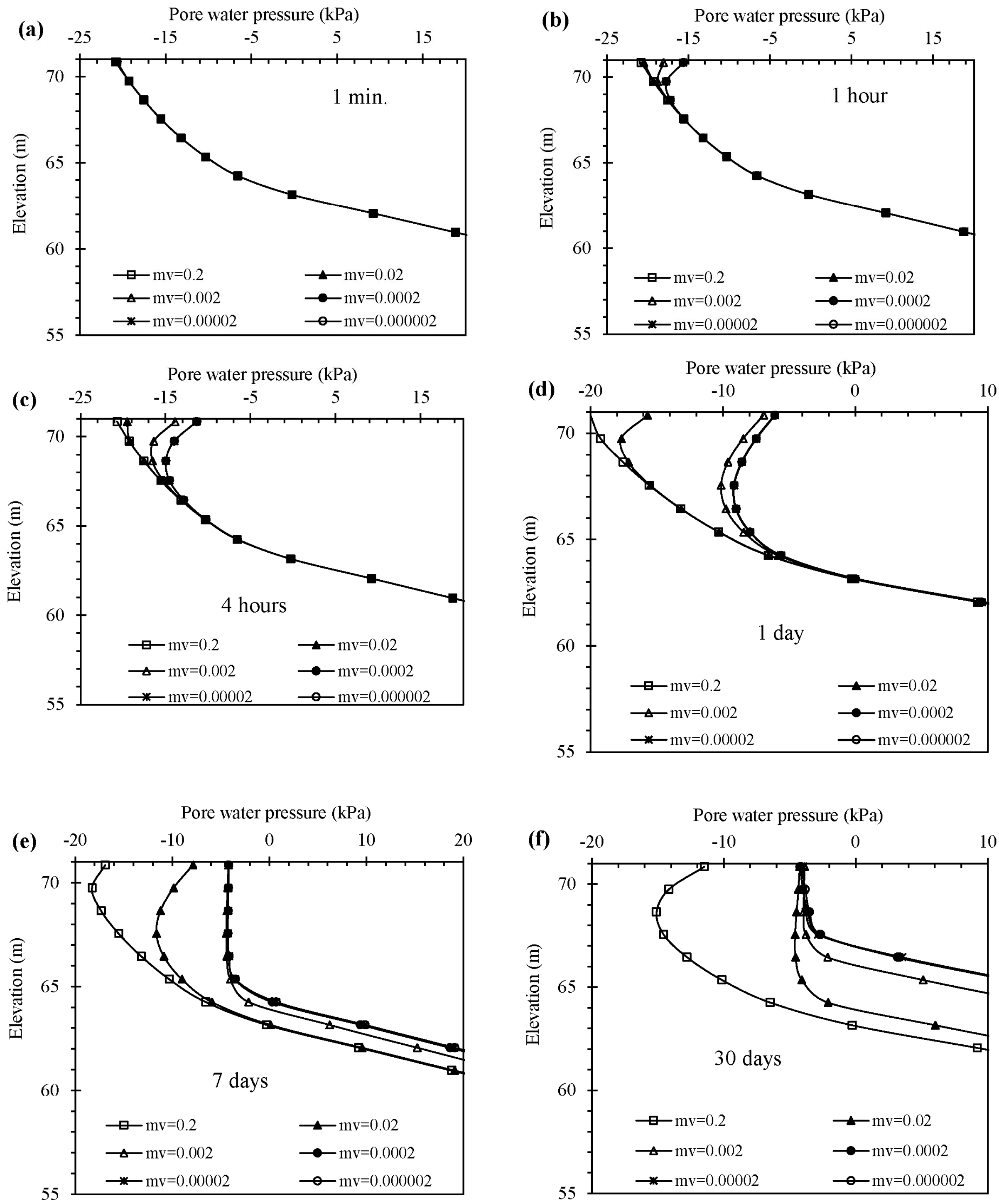
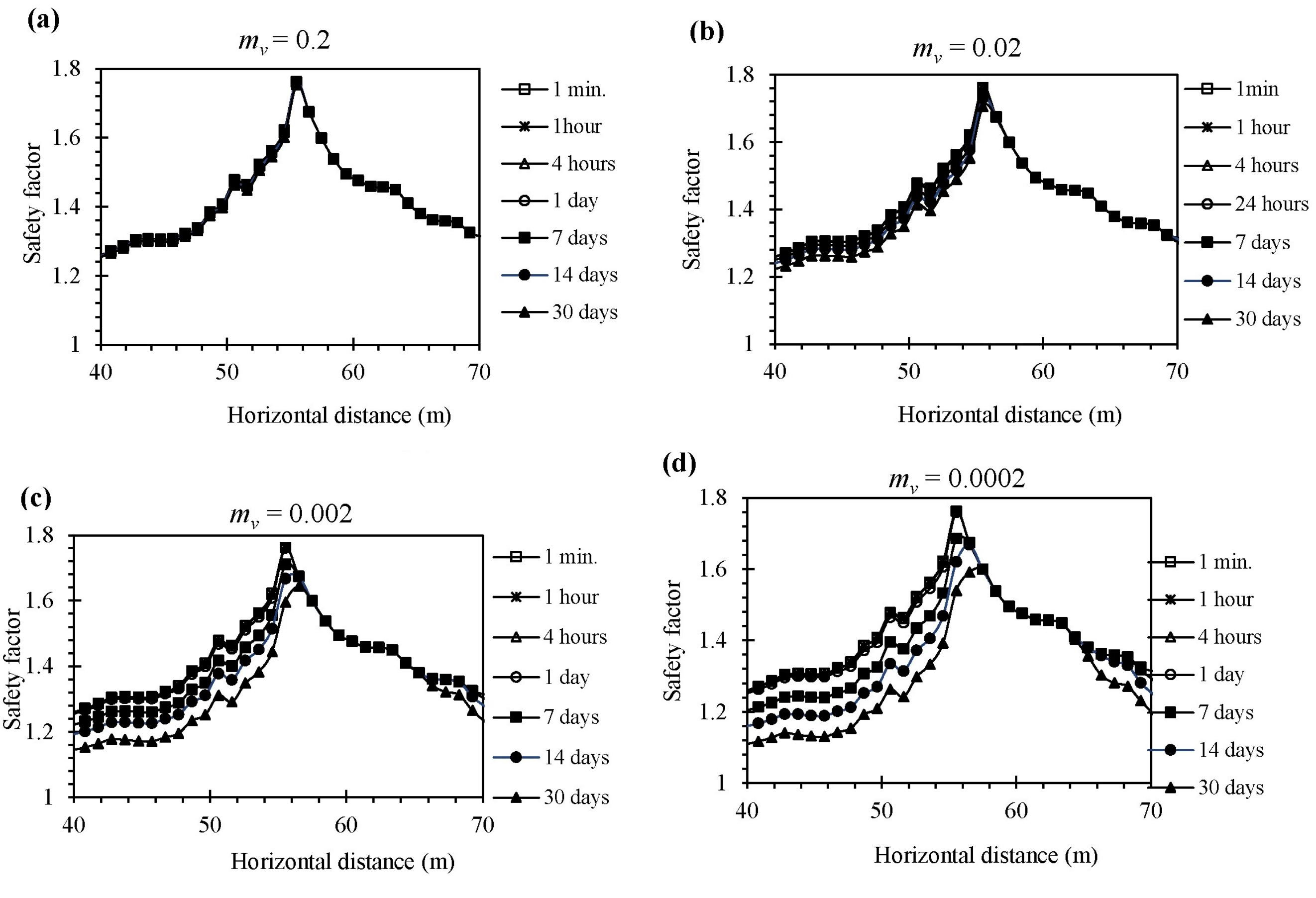


Figure 9. Pore water pressure for different rainfall durations and m_v values: (**a**) 1 min duration, (**b**) 1 h duration, (**c**) 4 h duration, (**d**) 1 day duration, (**e**) 7 days duration, (**f**) 30 days duration.

4.3. Stability of Consolidating Slope

Figure 10 illustrates the distribution of factor of safety along the slope (from the crest to the toe) for different values of mv and with the progression of infiltration. A close examination of the slope's stability indicates that the factor of safety tends to be less at both ends (crest and toe) compared to the middle of the slope for all values of mv. For an mv value of 0.2 kPa^{-1}, it is clearly seen that there is no difference in the factor of safety on the slope for all durations of rainfall. However, with an increase in soil compression, the factor of safety does appear to reduce with an increase in infiltration time across the different values of mv (from 0.02 to 0.000002 kPa^{-1}). This difference is slightly more pronounced (especially for antecedent rainfall with duration from 7 days to 30 days) as the degree of soil compression increases from an m_v of 0.002 to 0.000002 kPa^{-1}. Overall, the slope tends to be generally stable (factor of safety greater than one). It could be concluded that the existence of suction in the unsaturated portion of the slope under the rainfall durations investigated has ensured this possibility. In order to confirm this claim, the stability of the slope is further examined with the rainfall intensity increased by an order of 10 (i.e., q/k_s = 1) for a duration of 1 day to ensure full saturation. It could be observed from Figure 11 that for an m_v value of 0.2 kPa^{-1}, the minimum global factor of safety of the slope (1.234) for a lower intensity of rainfall (i.e, q/k_s = 0.1) is greater than the factor of safety for the slope subjected to higher intensity of rainfall (q/k_s = 1), which is 0.861. A factor of safety less than unity as indicated for the slope under higher rainfall indicates critical slope condition with impending failure.



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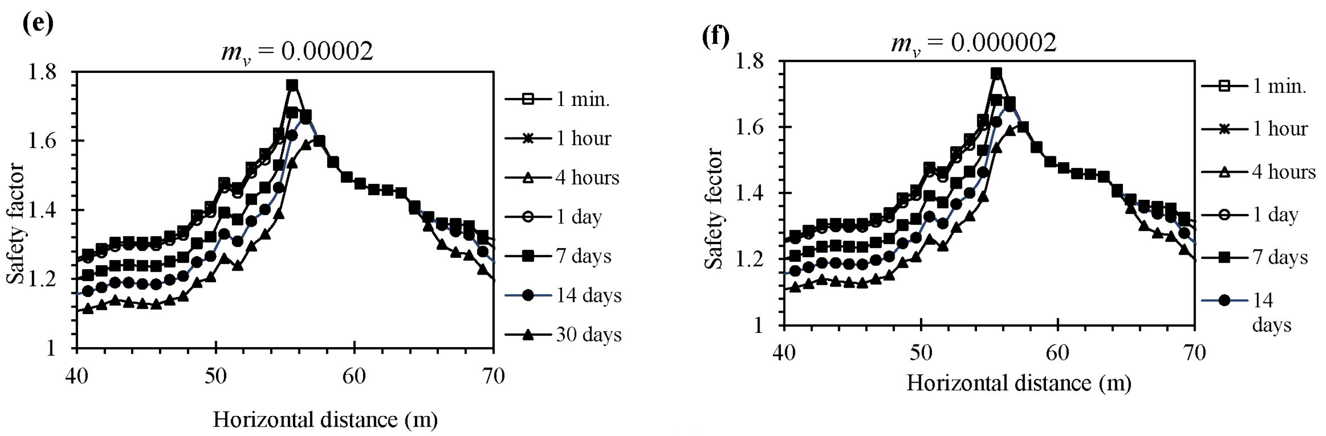

Figure 10. Safety factors along slope for under different rainfall durations and m_v values, where (**a**) m_v = 0.2, (**b**) m_v = 0.02, (**c**) m_v = 0.002, (**d**) m_v = 0.0002, (**e**) m_v = 0.00002, (**f**) m_v = 0.000002.

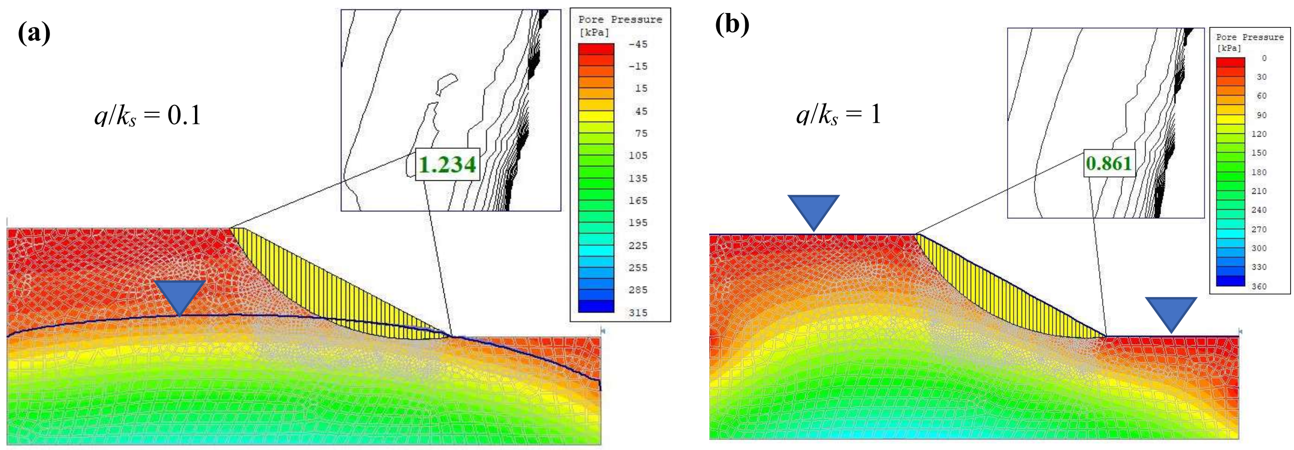

Figure 11. Minimum factor of safety on slope under different rainfall durations. (**a**) Minimum global factor of safety of the slope for intensity of rainfall (i.e, q/k_s = 0.1). (**b**) Minimum global factor of safety of the slope for intensity of rainfall (i.e, q/k_s = 1).

It is crucial to emphasize that impending failure of the slope would be critical with continuous rainfall infiltration duration beyond 30 days for a highly compressible soil, as Figure 11 indicates.

Figure 12 highlights the distribution of factor of safety with the duration of rainfall infiltration to buttress the points made above. As could be observed, for the slope with the least compressible soil, the factor of safety appears to remain constant for the entire duration of rainfall up to 30 days. The most drastic decrease in the factor of safety seem to occur with mv of soil beyond 0.02 kPa^{-1}. Although not obvious from the Figure 7 as seen previously, the effects of reducing the mv value of soil further from 0.0002 kPa^{-1} seem to be less as the factor of safety of the slope only changes slightly for the entire duration of the rainfall (please see Figure 12).

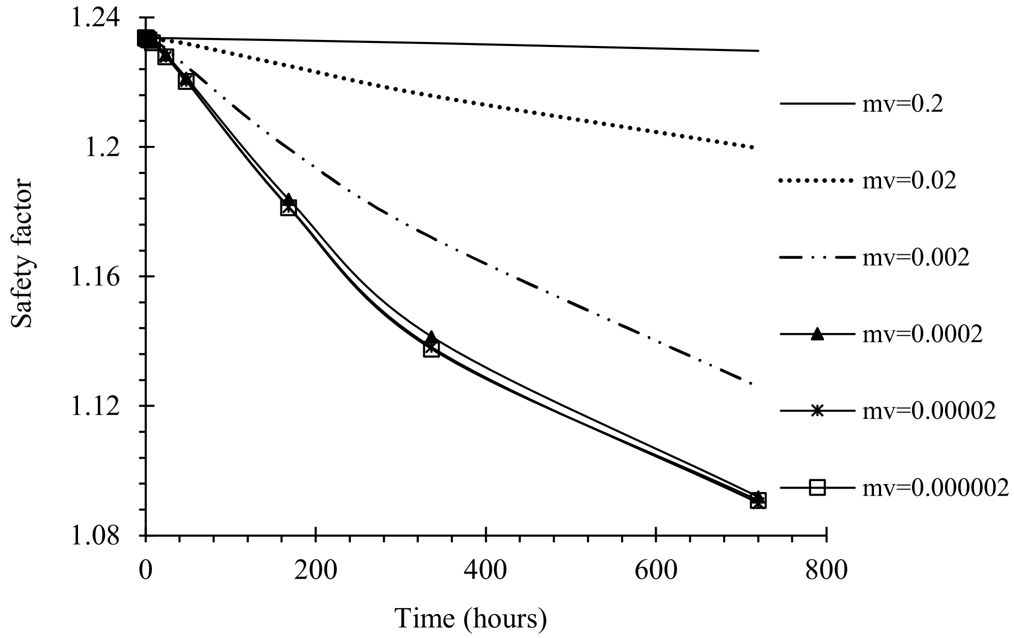

Figure 12. Factor of safety vs. rainfall durations for different m_v values.

5. Conclusions

This study examined the pore water pressure responses and stability of an unsaturated–saturated consolidating slope under the influence of rainfall infiltration. An analysis of slope behaviour was carried out with the results obtained for soils having similar saturated coefficients of permeability (k_s) of 1×10^{-5} m/s, SWCC fitting parameters (n_f of 2, and m_f of 1), and rainfall flux (q) of 1×10^{-6} m/s (i.e., q/k_s of 0.1) but with varying air-entry and coefficient of volumetric compression (mv) values. The following are major highlights of the study:

1. For the unsaturated portion of the slope (above the groundwater table), negative pore water pressure during rainfall infiltration less than the coefficient of permeability of the soil increases with the air-entry values of the soil, indicating the existence of suction in this region. However, as the time of rainfall progresses, the matric suction values tend to reduce with increasing air-entry values.
2. Generally, it is noticed that an increase in soil compressibility does tend to result in a decrease in soil suction above the rising groundwater level, irrespective of the advancing groundwater level for rainfall less than the saturated permeability of the soil and lasting for prolonged periods.
3. The difference in the pore water distribution profiles seems less for mv values below 0.002 kPa^{-1} especially for major rainfall events. Moreover, the distribution of the soil suction profile seems marginal for infiltration durations of 1 h to 4 h.
4. In terms of the stability of the slope, the factor of safety does appear to reduce with an increment in infiltration time as soil compression increases. This difference is slightly more pronounced (especially for antecedent rainfall with duration from 7 days to 30 days).
5. Although the slope appears to be just safe (factor of safety of 1.2) under the conditions of increased air-entry value, increased compression, and rainfall flux of 1×10^{-6} m/s, the stability of the slope can be compromised if the rainfall flux is equal to or greater than the saturated coefficient of permeability of the soil.

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References

1. UNFCCC Report of the Conference of the Parties Serving as the Meeting of the Parties to the Paris Agreement on Its Third Session, Held in Glasgow from 31 October to 13 November 2021. 2022. Available online: https://unfccc.int/documents/460952 (accessed on 15 December 2022).
2. Johnston, I.; Murphy, W.; Holden, J. A review of floodwater impacts on the stability of transportation embankments. *Earth Sci. Rev.* **2021**, *215*, 103553. [CrossRef]
3. Zhang, L.; Li, J.; Li, X.; Zhang, J.; Zhu, H. *Rainfall-Induced Soil Slope Failure: Stability Analysis and Probabilistic Assessment*; CRC Press: Boca Raton, FL, USA, 2016.
4. Collins, B.D.; Znidarcic, D. Stability Analyses of Rainfall Induced Landslides. *J. Geotech. Geoenviron. Eng.* **2004**, *130*, 362–372. [CrossRef]
5. Wu, L.; Huang, R.; Li, X. *Hydro-Mechanical Analysis of Rainfall-Induced Landslides*; Springer: Beijing, China, 2020.
6. Fredlund, D.G.; Rahardjo, H.; Fredlund, M.D. *Unsaturated Soil Mechanics in Engineering Practice*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2012.
7. Zhang, L.; Zhang, J.; Zhang, M.; Tang, W.H. Stability analysis of rainfallinduced slope failure: A review. *Proc. Inst. Civ. Eng. Geotech. Eng.* **2011**, *164*, 299–316. [CrossRef]
8. Cho, S.E.; Lee, S.R. Evaluation of Surficial Stability for Homogeneous Slopes Considering Rainfall Characteristics. *J. Geotech. Geoenviron. Eng.* **2002**, *128*, 756–763. [CrossRef]
9. Ng, C.W.W.; Wang, B.; Tung, Y.K. Three-dimensional numerical investigations of groundwater responses in an unsaturated slope subjected to various rainfall patterns. *Can. Geotech. J.* **2001**, *38*, 1049–1062. [CrossRef]
10. Lee, D.H.; Lai, M.H.; Wu, J.H.; Chi, Y.Y.; Ko, W.T.; Lee, B.L. Slope management criteria for Alishan Highway based on database of heavy rainfall-induced slope failures. *Eng. Geol.* **2013**, *162*, 97–107. [CrossRef]
11. Zhang, L.L.; Fredlund, D.G.; Zhang, L.M.; Tang, W.H. Numerical study of soil conditions under which matric suction can be maintained. *Can. Geotech. J.* **2004**, *41*, 569–582. [CrossRef]
12. Chui, T.; Freyberg, D. Implementing Hydrologic Boundary Conditions in a Multiphysics Model. *J. Hydrol. Eng.* **2009**, *14*, 1374–1377. [CrossRef]
13. Tsai, T.L.; Yang, J.C. Modeling of rainfall-triggered shallow landslide. *Environ. Geol.* **2006**, *50*, 525–534. [CrossRef]
14. Tsai, T.L.; Wang, J.K. Examination of influences of rainfall patterns on shallow landslides due to dissipation of matric suction. *Environ. Earth Sci.* **2011**, *63*, 65–75. [CrossRef]
15. Chen, J.-M.; Tan, Y.-C.; Chen, C.-H. Multidimensional Infiltration with Arbitrary Surface Fluxes. *J. Irrig. Drain. Eng.* **2001**, *127*, 370–377. [CrossRef]
16. Zhang, L.M.; Li, X. Microporosity Structure of Coarse Granular Soils. *J. Geotech. Geoenviron. Eng.* **2010**, *136*, 1425–1436. [CrossRef]
17. Yuan, F.; Lu, Z. Analytical Solutions for Vertical Flow in Unsaturated, Rooted Soils with Variable Surface Fluxes. *Vadose Zone J.* **2005**, *4*, 1210–1218. [CrossRef]
18. Tsaparas, I.; Rahardjo, H.; Toll, D.G.; Leong, E.C. Controlling parameters for rainfall-induced landslides. *Comput. Geotech.* **2002**, *29*, 1–27. [CrossRef]
19. Childs, E.C.; Collis-George, N. The permeability of porous materials. *Proc. R. Soc. Lond. A* **1950**, *201*, 392–405.
20. Fredlund, D.G.; Morgenstern, N.R. Constitutive relations for volume change in unsaturated soils. *Can. Geotech. J.* **1976**, *13*, 261–276. [CrossRef]
21. Fredlund, D.G.; Xing, A. Equations for the soil-water characteristic curve. *Can. Geotech. J.* **1994**, *31*, 521–532. [CrossRef]
22. Rocscience. Slide2 Modeler: 2D Limit Equilibrium Analysis for Slopes 2022. Available online: https://www.rocscience.com/software/slide2 (accessed on 8 August 2022).

23. Lee, L.M.; Gofar, N.; Rahardjo, H. A simple model for preliminary evaluation of rainfall-induced slope instability. *Eng. Geol.* **2009**, *108*, 272–285. [CrossRef]
24. Knappett, J.; Craig, R.F. *Craig's Soil Mechanics*, 8th ed.; Spon Press: Abingdon, UK, 2012.