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EFFECT OF SURFACE BOUNDARY CONDITION ON RAINFALL INFILTRATION

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Abstract. Rainfall infiltration is greatly influenced by the surface boundary condition as well as hydraulic properties of soil. This paper highlights the study on the effect of several surface boundary conditions on the rainfall infiltration using a computer program VADOSE/W. A parametric study was carried out to study the effect of ambient temperature, relative humidity and wind speed on the evaporation and rainfall infiltration rate. The effect of soil hydraulic conductivity on the mechanism of rainfall infiltration was also studied by using two soil column models. Results show that rainfall infiltration is sensitive to relative humidity and ambient temperatures lower than soil temperature, but insensitive to wind speed and ambient temperatures higher than soil temperature. The hydraulic conductivity of soil and rainfall intensity have great influence on the infiltration mechanism and the development of surface runoff. Thus, reliable saturation profile can only be achieved if accurate surface boundary condition was considered for analysis.

Keywords: Rainfall infiltration, evaporation, boundary condition, hydraulic conductivity, soil column model

Abstrak: Penyusupan air hujan amat dipengaruhi oleh keadaan sempadan permukaan tanah dan sifat-sifat hidraulik tanah. Kertas kerja ini mengetengahkan kajian mengenai kesan beberapa keadaan sempadan permukaan tanah terhadap penyusupan air hujan dengan menggunakan satu program komputer VADOSE/W. Satu kajian parametrik dijalankan untuk mengkaji kesan suhu persekitaran, kelembapan relatif udara, dan kelajuan angin terhadap penyejatan dan kadar penyusupan air hujan. Kesan konduktiviti hidraulik tanah terhadap mekanisma penyusupan air hujan juga dikaji dengan menggunakan dua model tiang tanah. Keputusan menunjukkan penyusupan air hujan adalah sensitif terhadap kelembapan relatif udara dan suhu persekitaran yang lebih rendah daripada suhu tanah, tetapi tidak sensitif terhadap kelajuan angin dan suhu persekitaran yang lebih tinggi daripada suhu tanah. Konduktiviti hidraulik tanah dan keamatan hujan mempunyai pengaruh yang besar terhadap mekanisme penyusupan dan pembentukan air larian permukaan. Maka, profil ketepuan tanah yang meyakinkan hanya boleh diperolehi jika keadaan sempadan permukaan tanah yang tepat dipertimbangkan dalam analisis.

Kata kunci: Penyusupan air hujan, penyejatan, keadaan sempadan, konduktiviti hidraulik, model tiang tanah

1.0 INTRODUCTION

Rainfall infiltration estimation is important for slope stability assessment especially for countries in tropical region where the annual rainfall is considerably high. The infiltration rate of a particular soil slope is affected by several intrinsic and

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extrinsic factors. The intrinsic factors affecting the infiltration rate are the hydraulic conductivity function, water retention characteristics and soil thermal function. The extrinsic factors mainly refer to climatic conditions, such as rainfall intensity and duration, rainfall pattern, ambient temperature, relative humidity, wind speed and vegetation properties.

The infiltration and seepage process of rainfall into unsaturated and saturated soil regime have been studied by several researchers. Green and Ampt [1] first proposed an infiltration model to correlate the depth of the wetting front during rainfall infiltration with the hydraulic conductivity, K_{sat}. As the application of the computer and numerical software become increasingly popular, Fei and Keizo [2] considered more parameters such as hydraulic characteristics, initial relative degree of saturation, and rainfall intensity and duration in their numerical studies on the effects of rainfall infiltration on pore-water pressure in unsaturated slopes and hence on slope stability. Zhan and Ng [3] performed an analysis to study the mechanism of rainfall infiltration in unsaturated soil. They concluded that saturated hydraulic conductivity K_{sat} controls the water coefficient of permeability within a lower negative pore-water pressure range; hence it dominates in an infiltration system. Furthermore, Benson *et al.* [4] compared the field data with the predictions made by using two numerical models: UNSAT-H and VADOSE/W for an evapotranspiration cover. Their study demonstrated that more accurate predictions were obtained with VADOSE/W than UNSAT-H.

Fredlund and Rahardjo [5] stated that rainfall infiltration is actually affected by the surface boundary condition such as vapour pressure because it influences the rate of condensation while evaporation rate depends only on temperature. Under such circumstance, thermal properties include initial soil temperatures, thermal conductivity function and volumetric specific heat function become important parameters in rainfall infiltration analysis. These thermal properties influence the vapour pressure distribution, but not the water content and pore-water-pressure distributions. Higher temperature in the soil will lead to higher vapour pressure, and vice versa.

Evaporation and transpiration have been increasingly recognised as important factors in the infiltration process, however, inclusion of these variables in rainfall infiltration computation in practice is still limited.

This study is focused on the evaluation of the effect of surface boundary conditions on the rainfall infiltration through soil. Parametric study was conducted to identify the effect of several factors namely rainfall intensity, ambient temperature, relative humidity, and wind speed on the evaporation, surface runoff and rainfall infiltration rate, and to indicate the dominant factors in their contribution to rainfall infiltration process.

2.0 METHOD OF ANALYSIS

In order to investigate the infiltration pattern and volumetric water content in soil profile, a one-dimensional transient analysis was carried out with the aid of finite element technique based numerical modeling software. The analysis was limited to vertical infiltration, neglecting the side boundary effect and the horizontal water flow. A 3m-deep soil column was simulated with boundary condition of zero flow (Q = 0) applied on the peripheral boundaries (Figure 1). Initial water table was specified at a depth of 2 m from the top of the soil column. Precipitation occurs from the top soil surface to the impermeable bottom boundary. Hydrostatic pore-water pressure distribution was assumed for the initial pore-water pressure condition in all analyses.

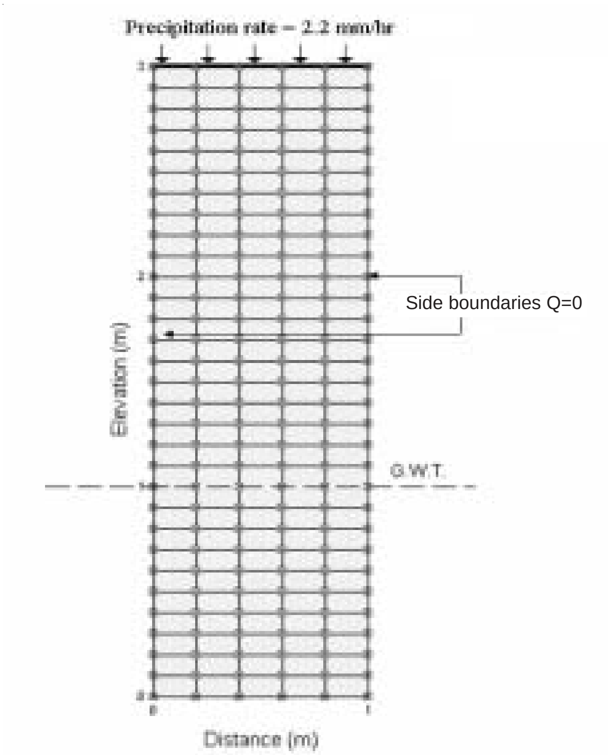


Figure 1 Soil column model for one-dimensional transient analysis

Initially, the response of uniformly graded sand with saturated hydraulic conductivity, $K_{sat} = 2.15 \times 10^{-5}$ m/s to the rainfall infiltration was observed from the soil column model. Precipitation rate of 2.2 mm/hr was applied from the top of the soil for a period of 12.5 hour to simulate the typical continuous long duration rainfall with a low intensity which is a typical rainfall characteristic in Peninsular Malaysia during the monsoon season [7]. The other climatic data used in the analysis were also the typical mean values for Peninsular Malaysia, i.e. ambient temperature = 27^{o}C, relative humidity = 85% and wind speed = 3.0 m/s.

The analyses were carried out to evaluate the effect of some surface boundary conditions, i.e. ambient temperature, relative humidity and wind speed to the evaporation and infiltration rate by using computer software VADOSE/W [6]. The software is a comprehensive infiltration modeling tool that accounts for precipitation (*P*), actual evaporation (*AE*), actual transpiration (*AT*), runoff (R), and storage (*S*). Theoretically, the equation of equilibrium is written as:

$$P - AE - AT - R - S = 0 \quad (1)$$

However, due to the convergence error which is hardly prevented in most of the finite element technique based software, VADOSE/W introduces a parameter, called water balance (WB) into the equilibrium equation. WB represents the residual water or loss of water resulted from the entire infiltration system:

$$P - AE - AT - R - S = WB \quad (2)$$

The introduction of WB parameter has minimised the convergence error in finite element analysis while at the same time facilitates the users to evaluate the quality of the computed results.

Further analyses were carried out to study the relationship between hydraulic conductivity and surface runoff. The effects of hydraulic conductivity function and precipitation rate on the surface runoff and infiltration rate were studied by comparing the response of sand and clay soil column under equal rainfall intensity. In this case, the saturated hydraulic conductivity (K_{sat}) of clay is 2.5×10^{-8} m/s. The study was carried out under equal precipitation rate where ponding was not allowed at the top of the soil surface if influx boundary was greater than the saturated hydraulic conductivity.

3.0 RESULTS AND DISCUSSION

Initial study shows that assuming there is no surface boundary conditions applied, the infiltration rate eventually reaches maximum value of 2.2 mm/hr equal to the precipitation rate. Figure 2 shows the effects of ambient temperature, relative humidity, and wind speed on evaporation rate. In this figure, the variables were set to deviate from mean values and the slopes of the lines indicate the degree of sensitivity for each parameter. Steeper lines correspond to more sensitive parameters and vice versa. The results show that the infiltration is sensitive to the ambient temperature lower than soil temperature, but less sensitive to ambient temperature higher than soil temperature. Note that usually ambient temperature is lower during rainfall and hence more water infiltrate into the soil. Steven *et al.* [8] in their observation at Western Pacific found that the ambient temperature dropped from 4.8 to 5.8 ^{o}C during the rain. Thus the accurate input of ambient temperature is important for the analysis. Figure 2 also shows that the infiltration is considerably sensitive to relative humidity but not to wind speed, hence the accuracy in wind speed data measurement is not crucial in estimating the infiltration rate.

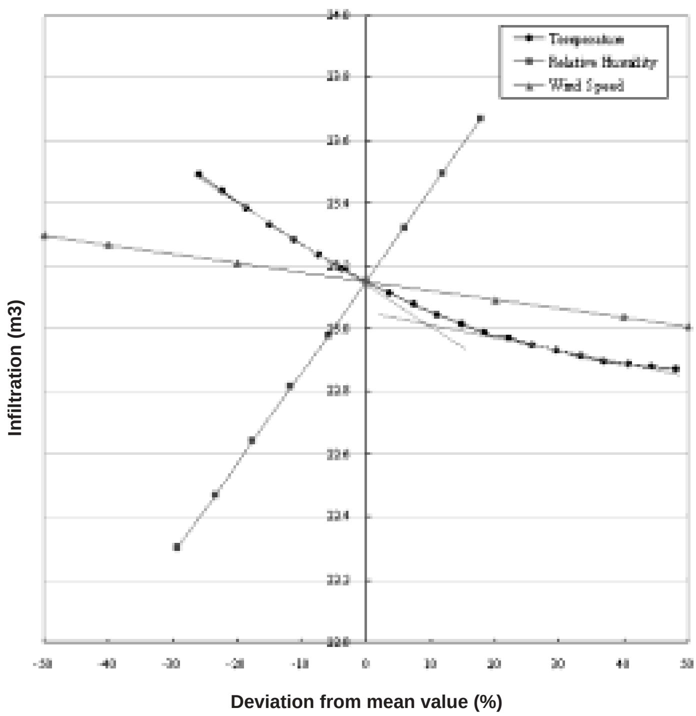
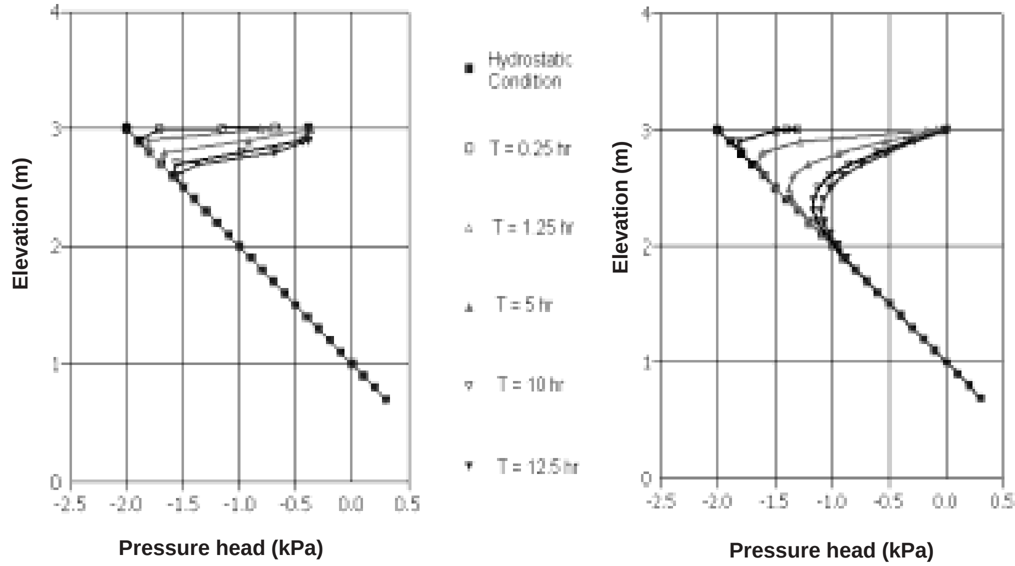


Figure 2 Sensitivity of infiltration rate to surface boundary conditions

Figures 3 and 4 show the results of analysis on the effect of hydraulic conductivity on rainfall infiltration process in terms of pressure head and saturation profile for both sand and clay models. In these models, the surface runoff takes place if the soil surface has achieved full saturation.

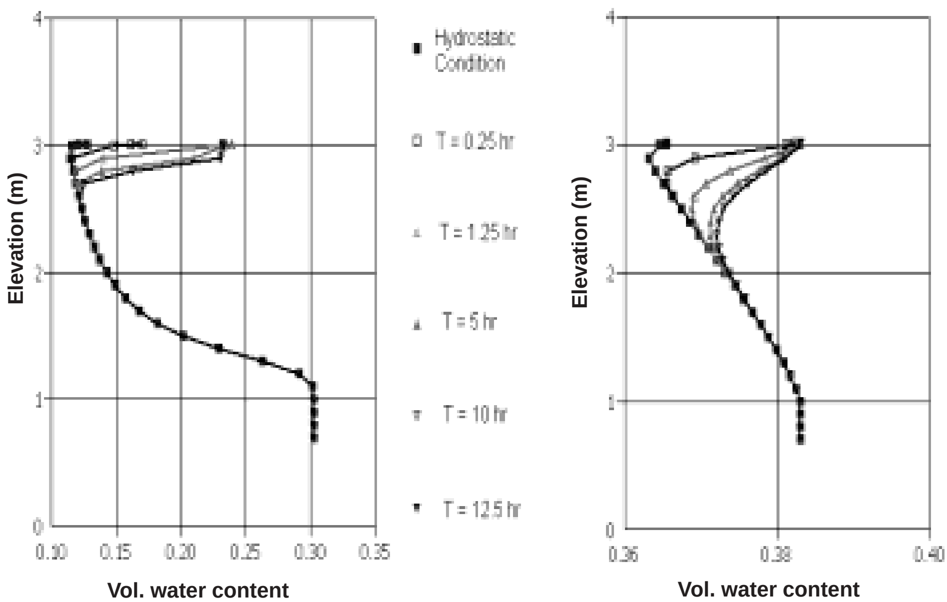
For sand column with saturated hydraulic conductivity higher than rainfall intensity, full saturation is unlikely to happen within short duration. This can be observed from Figures 3(a) and 4(a) that wetting front has not formed even after 12.5 hours of rainfall. This is because water infiltrates easily to deeper portion of soils and not just accumulating near the soil surface. Under such condition, the possible mechanism for surface runoff to occur is when the water table or perched water table has risen to soil surface in which no further infiltration is allowed.

On the other hand, clay soil column with hydraulic conductivity lower than rainfall intensity demonstrated that surface runoff occurs once the soil reached fully saturated condition. Saturation was reached in less time because the water



(a) Sand (K_{sat} = 2.15×10^{-5} m/s) (b) Clay (K_{sat} = 2.5×10^{-8} m/s)

Figure 3 Pressure head profile for soil column model: (a) sand and (b) clay



(a) Sand (K_{sat} = 2.15×10^{-5} m/s) (b) Clay (K_{sat} = 2.5×10^{-8} m/s)

Figure 4 Volumetric water content profile for soil column model: (a) sand and (b) clay infiltrated into the soil take longer time to drain. Figures 3(b) and 4(b) show that in clay soil column, the soil surface reached fully saturated condition only after 1.25 hour of rainfall, hence less rainfall water is infiltrated into the soil.

Although less water is infiltrated into the soil with low hydraulic conductivity, the great reduction in matrix suction is observed. On the other hand, large volume of rainfall water infiltrates into the soil with high hydraulic conductivity, but water does not accumulate near the soil surface. The water flows into deeper soil regime and leads to the rise in ground water table. The phenomena can be explained with the soil water characteristic curve (SWCC) of soil which represents the ability of the soil particles to hold the water.

4.0 CONCLUSIONS

Parametric study was carried out on the effect of surface boundary conditions such as ambient temperature, relative humidity and wind speed as well as the effect of hydraulic conductivity of the soil on the mechanism of rainfall infiltration. The following conclusions can be drawn:

(i) Surface boundary conditions should be considered for more accurate analysis of rainfall infiltration into and seepage through the soil. Thus, VADOSE/W program that has the ability to simulate the boundary conditions appears to be a more suitable analysis tool for transient analysis.

(ii) Evaporation is sensitive to relative humidity, but relatively insensitive to wind. Moreover, the evaporation rate is only sensitive to the ambient temperature if the temperature is lower than the soil temperature. Since this is normally the case, accurate input on the ambient temperature and relative humidity is necessary for the estimation of rainfall infiltration.

(iii) Soil with low hydraulic conductivity tends to form full saturation near the soil surface and allows less water to infiltrate into the soil. Despite less water is infiltrated into the soil with low hydraulic conductivity, the greater reduction in matrix suction is observed as compared to the soil with high hydraulic conductivity. Thus, besides the hydraulic conductivity, other hydraulic properties of soil such as soil water characteristic curve (SWCC) should be accounted for in the rainfall infiltration analysis.

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