Parameter Optimization of Conceptual Tank Model for Groundwater Level Prediction

Soon Min Ng, Mohd Ashraf Mohamad Ismail and Ismail Abustan

Abstract Groundwater is regarded as one of the critical factors that can affect slope stability. Thus, groundwater levels may render useful information regarding the stability conditions of a slope. This preliminary study focused on developing a simple and quick analytical tool to evaluate the groundwater levels due to rainfall for slope stability assessment. To achieve this objective, a well-established rainfall-runoff model known as tank model was adopted in this study. An instrumented soil slope located in Malaysia was used as the case study to investigate the effectiveness of the proposed approach. Rainfall and groundwater levels data for a period of 8 months were used to calibrate the tank model unknown parameters representing runoff, infiltration, groundwater flow and head. The tank model was able to produce a satisfactory root mean square error (RMSE) of 0.185 for the computed groundwater levels compared to the observed groundwater levels. To produce a more accurate prediction, it is recommended to utilize the multi tank models that are position at crest, middle and toe of the slope. An accurate groundwater levels prediction will contribute to a reliable slope stability analysis which is valuable for the landslide early warning system applications.

Keywords Groundwater level prediction · Tank model · Slope stability · Rainfall induced slope failure

S. M. Ng
School of Energy, Geoscience, Infrastructure and Society, Heriot-Watt University Malaysia, Putrajaya, Malaysia

M. A. M. Ismail (✉) · I. Abustan
School of Civil Engineering, Universiti Sains Malaysia (USM), Engineering Campus, Pulau Pinang, Malaysia
e-mail: ceashraf@usm.my

F. Mohamed Nazri (ed.), *Proceedings of AICCE'19*, Lecture Notes in Civil Engineering 53, https://doi.org/10.1007/978-3-030-32816-0_60

1 Introduction

Rainfall has been recognized as the major triggering factor of slope failure worldwide and also in Malaysia [8]. Rainwater can either infiltrates into the slope or become surface runoff when fall onto the slope. The infiltrated rainwater may increase the existing groundwater level developing two different zones namely unsaturated and saturated zone. Groundwater plays an important role in affecting the stability of a slope. Intense rainfall may raise the groundwater level resulting in a lower matric suction and increased pore water pressure. This will subsequently reduce the shear resistance of the soil and slope failure will be triggered if the shear resistance is exceeded. Therefore, the prediction of groundwater level may render a beneficial outcome on the forecast of a landslide occurrence.

The commonly used techniques to predict rainfall induced slope failure are rainfall threshold and in situ instrumentation. Rainfall threshold can be defined as the minimum amount of rainfall that, when reached or exceeded, are likely to trigger failure [9]. Rainfall thresholds for slope failure initiation can be established by the study of rainfall events that have already resulted in slope failure. However, this approach may not be feasible to other areas due to the differences in climate, lithological and morphological conditions [2].

The in situ monitoring instrumentation offers an alternative that observe the changes of certain parameters with time to detect early indications of catastrophic movement since slope failure does not occur instantaneously. Knowledge regarding internal soil moisture and piezometric responses is the key to an effective prediction of the rainfall induced slope failure [1]. Piezometers and tensiometers can be used to measure the positive and negative pore water pressure within the slope mass respectively. These parameters are most indicative for the early stage of slope instability induced by rainfall [4]. Hong and Wan [3] also suggested that potentially failure prone slopes require a realistic estimation of maximum groundwater table. Hence, evaluating the response of groundwater table is the first step to identify the stability conditions of a slope. This study aims to develop a simple and quick tool to evaluate the groundwater table fluctuations in a slope subjected to rainfall. To achieve this objective, an established rainfall-runoff model known as the tank model will be adopted in this study.

2 Tank Model

Tank model was developed by Sugawara in 1995 as a rainfall-runoff model for the application in hydrological studies [10]. The concept mimics the rainfall-runoff process by using individual tank laid in series to represent the water movement among the storages as illustrated in Fig. 1. The model shows that the rainfall on an area can be divided into two main components namely surface runoff and base flow. The surface runoff occurs immediately after rainfall whereas base flow, in which

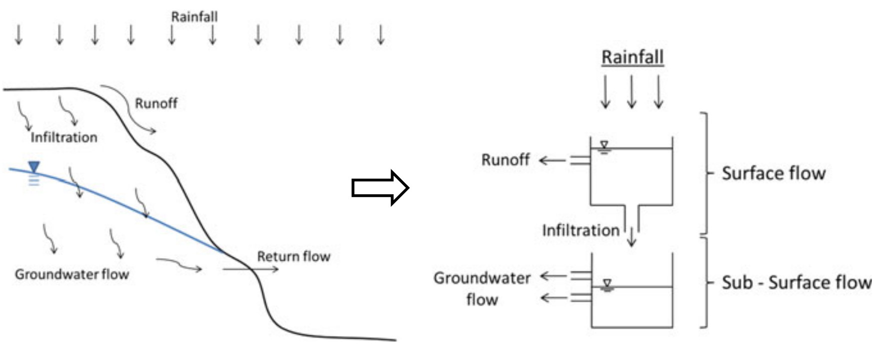

Fig. 1 Conceptual tank model [10]

rainwater infiltrated into the subsurface and then appears in surface as groundwater base flow.

Many hydrologists are using this model due to the concept simplicity and computation while achieving forecasting accuracy compared to other complicated models. In Malaysia, tank model has been adopted as the flood forecasting model for Sungai Kelantan in 1981 and Sungai Kuantan in 2004 [7]. Koyama et al. [5] has revolutionized the tank model concept where multiple tank models that considered the input and output of water into or out of the slope system was introduced. The study has successfully been implemented on a case study in Japan that enable a reliable representation of water mass balance in the slope. This shows that tank model concept has a great potential to be utilized as a groundwater level evaluation tool for slope stability assessment.

3 Case Study

An instrumented soil slope located in Malaysia was used as the case study to investigate the effectiveness of the proposed tank model approach. The tank model consists of two layers known as the upper and lower tanks. The upper tank acts for surface runoff and infiltration while the lower tank for underground flow and groundwater level. Each tank has outlets on its bottom and vertical sides to determine the volume of water flowing out from the tank. Hence, equations are required to represent the water movement between the tanks.

The related parameters assigned for the tank model system are illustrated in Fig. 2. The discharge coefficient of each outlet is symbolized by α_1 for runoff, β_1 for infiltration and α_2 for groundwater flow. The volume of water leaving each tank depends on the discharge coefficients and the gap between water level on each tank with head controls for each outlet which consist of H_1 for runoff and H_2 for groundwater flow. The amount of surface runoff, Q_1, groundwater flow, Q_2 and infiltration, I_1 can be expressed as:

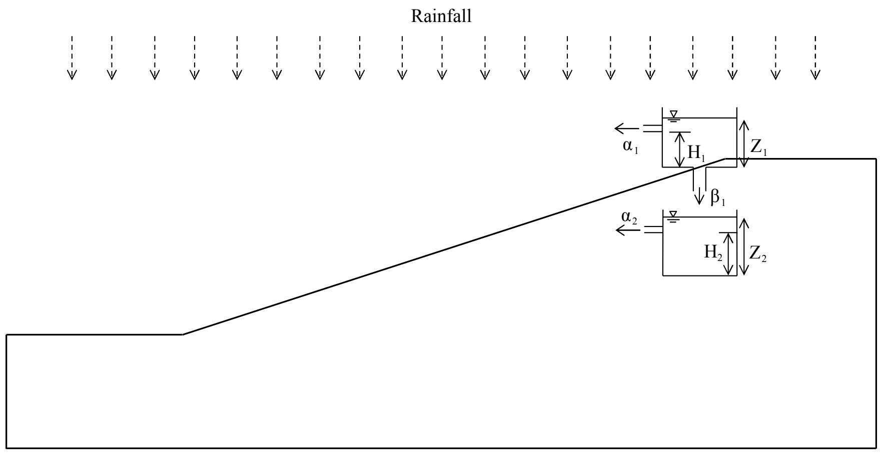

Fig. 2 The tank model system on slope and the unknown parameters

$$Q_1 = \alpha_1 \times (Z_1 - H_1) \tag{1}$$

$$I_1 = \beta_1 \times Z_1 \tag{2}$$

$$Q_2 = \alpha_2 \times (Z_2 - H_2) \tag{3}$$

where, Z_1 and Z_2 is the water level in the upper and lower tank respectively.

According to the water balance theory at a specific time, the water level in the tank can be evaluated as follows:

$$Z_1(t) = Z_1(0) + I + E - I_1 - Q_1 \tag{4}$$

$$Z_2(t) = Z_2(0) + I_1 - Q_2 \tag{5}$$

where $Z_i(0)$ is the initial water level, I is the rainfall intensity and E is the evaporation rate. The water level for the lower tanks Z_2 is related to the groundwater level. Hence, the groundwater level at a specific time, $GWT_c(t)$ can be computed by using this equation:

$$GWT_c(t) = GWT_{ref} + \frac{Z_2}{n} \tag{6}$$

where GWT_{ref} is the initial groundwater level which is equivalent to 13.3 m and *n* is the soil porosity which has the value of 0.2. Calibration for the tank model parameters were carried out using the rainfall intensity data and in situ groundwater levels at the crest of the slope as presented in Fig. 3. The calibration process was executed using the optimization function technique in Microsoft Excel by minimizing the difference between the computed and observed groundwater levels.

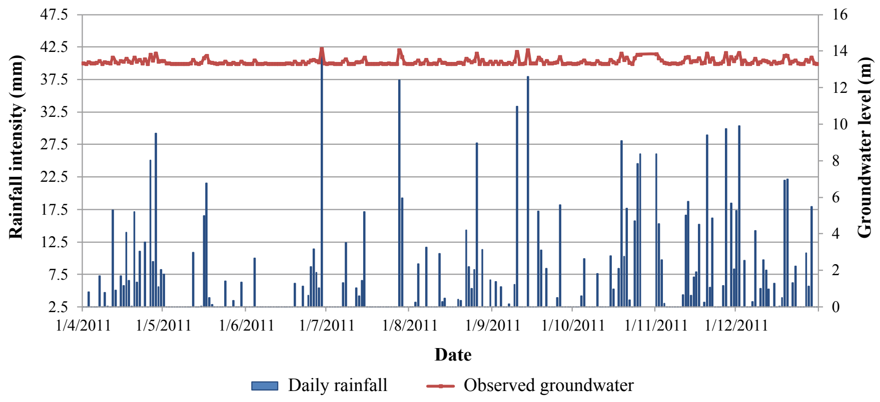

Fig. 3 Daily rainfall intensity and groundwater level records in year 2011

Thus, the RMSE value will be used as an indicator to evaluate whether the prediction value fits the observed value. This process offers the advantages of producing more refined values and require less computation time compared to the conventional trial and error method [6].

4 Results and Discussion

The data period from 1st April 2011 to 31st December 2011 was utilized to determine the best fit between the observed and computed groundwater levels. Table 1 summarized the result of parameter calibration using the optimization method. The discharge coefficients of α_1 showed a value of 0 that signified no runoff will occur at the crest of the slope. From the discharge coefficient of infiltration value, β_1, and groundwater flow value, α_2, it can be observed that the infiltration and groundwater flow occur at the crest of the slope due to rainfall. Figure 4 presents the results of the computed groundwater levels based on the calibrated tank model. The groundwater levels were seen to fluctuate correspond to the daily rainfall intensity. The accuracy and performance of the computed model can then be assessed by using the RMSE value calculated by the equation below:

$$Root\ mean\ square\ error\ (RMSE) = \sqrt{\frac{\sum_{i=1}^{m} [(GWT_c) - (GWT_o)]^2}{M}} \qquad (7)$$

For this study, the computed groundwater level at the crest of the slope is close to the observed groundwater levels with RMSE of 0.185. This value indicates a satisfactory performance by the tank model in evaluating the groundwater levels

Table 1 Calibrated tank model parameters

Symbol	Parameter
α_1	0.000
α_2	0.550
β_1	4.000
H_1	0.005
H_2	0.005
Z_1	0.010
Z_2	0.010

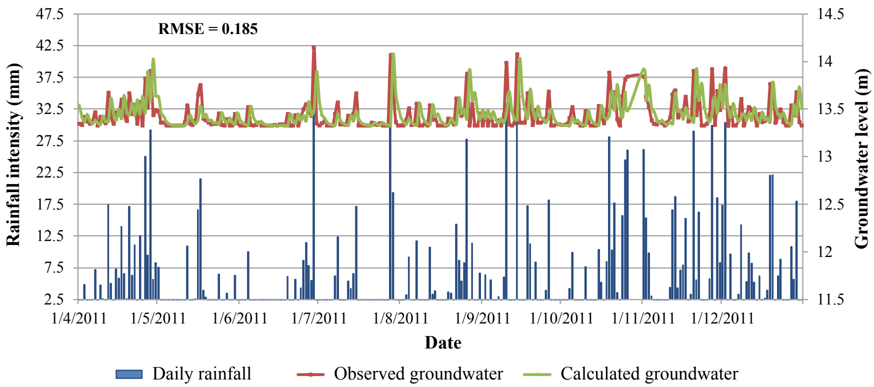

Fig. 4 Parameter calibration result for the calculated groundwater levels at the crest of the slope

fluctuations due to rainfall. However, it can be observed that there are some minor discrepancies at 1/04/2011 due to the initial calibration process of the tank model to learn and train with the given data. In order to have a better fit of the computed groundwater levels with the observed values, it is recommended to apply additional tank models at the middle and toe of the slope as shown in Fig. 5. This is to ensure that the water mass balance system for the slope is entirely taken into consideration. More input data should also be used to calibrate the unknown tank model parameters so that the accuracy of the predicted model can be increased. Subsequently the calibrated tank model parameters can be utilized to evaluate the groundwater levels at time ahead using forecasted rainfall intensity for landslide early warning system.

5 Conclusion

A simple and quick analytical tool of using the conceptual tank model that can evaluate the groundwater level fluctuation due to rainfall has been developed in this study. A set of unknown parameters has been calibrated with the in situ monitoring

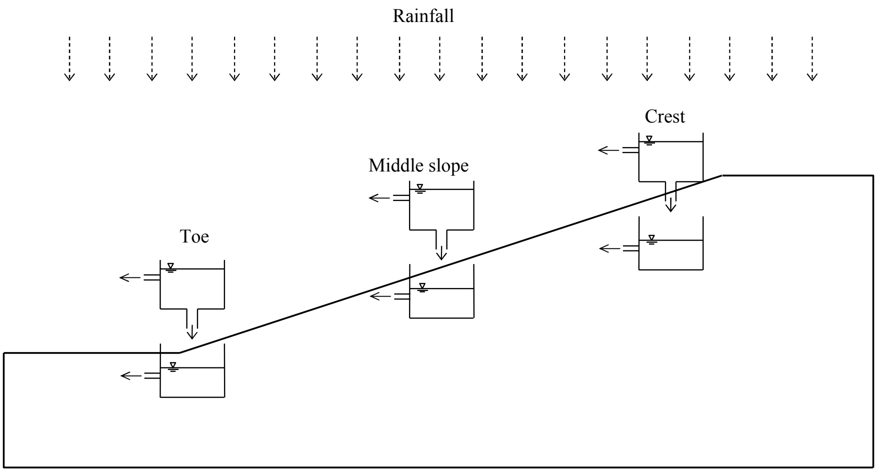

Fig. 5 Application of tank models in slope system

groundwater levels that is able to replicate the water mass balance system of the slope model. The tank model produced a RMSE value of 0.185 which indicates satisfactory accuracy between the observed and computed groundwater levels at the crest of the slope. This study can be further enhanced by adding additional tank model to the middle and toe of the slope to form a multi tank model system. Besides, the performance of other global optimization methods such as Genetic Algorithms (GA), Simulated Annealing (SA) and Artificial Neural Network (ANN) should also be investigated in order to determine a robust and efficient parameters optimization method. These recommendation will be able to comprehensively examine the groundwater response due to rainfall that is essential for slope stability assessment.

Acknowledgements The authors would like to express their appreciation to Bridging Grant of Universiti Sains Malaysia (304 111/PAWAM/6316314) for the financial support to carry out this research.

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