Stability of Railway Embankment in Saturated and Unsaturated Conditions

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Abstract- Slope failure is a vital issue in civil engineering infrastructures. Besides, climate change implications made this problem more critical. Therefore, in this study, a railway embankment's slope stability has been studied in saturated and unsaturated conditions. The soil sample was collected from Universiti Teknologi Malaysia, Johor Bahru. The necessary and required data obtained through lab experiments. The obtained data from lab experiments then used in Seep/W and Slope/W to model the railway embankment numerically. The results obtained from this study indicate that rainfall infiltration plays a vital role in the safety factor value. The obtained results also depicted that both rainfall intensity and duration play an important role in slope stability. The factor of safety showed a declining pattern with increasing rainfall and duration of rainfall. The safety factor decrement occurred since the matric suction was reduced (negative pore water pressure) by rainfall infiltration. Besides, the safety factor decrease was more acute when train load was applied in a rainy period. Thus, it is suggested that in a long period of rainy time, the railway authorities should stop the train operation, or the embankment stability should be increased using some stabilization methods in the planning and designing stage.

1. Introduction
Climate change implications can be seen in varying ways. One of these implications is the changing rainfall pattern, one of the most critical factors in slope instability. Generally, in all parts of the world and particularly in tropical regions, rainfall-induced landslides and slope failure are the most common [1, 2]. The sustainability in urban living may be affected by slope instability caused by rainfall [2]. Although most natural and human-made slopes are in unsaturated conditions, the influence of matric suction on slope stability analysis is mainly ignored in studies. The vanishing of negative pore water pressure with increasing moisture content and infiltrated rainfall is counted as one of the main reasons for matric suction to be ignored in slope stability analysis. However, the matric suction can be maintained by adopting some measures such as slope surface cover and surface compaction to minimize the infiltrated rainfall water [3].

The railway embankment is typically in unsaturated condition because of its height from the ground surface and deep water table. However, during the rainy seasons, the embankment soil condition changes from unsaturated to saturated condition. The location of the water table may be shifted from a down position toward the ground surface. In the rainy season, the prevention of entering water into the ballasted railway track layers is roughly impossible [4]. The embankment, therefore,
experiences cyclic wetting and drying condition during its service life. Thus, this cyclic change of soil conditions results in decreased shear strength. The shear strength along a potential failure surface in a slope can be reduced with infiltrated rainfall water [5]. In this regard, Zi-Zhen et al. [6] stated that decreased soil cohesion plays the leading role in most short-term slope failures. The slope failure may be happened either by rising phreatic level or directly by infiltrated rainfall [7].

In regard to the rainfall impacts, numerous researches have been conducted on slope stability worldwide [8-12]. The influence of rainfall on slope stability has been studied through field instrumentation [9], laboratory-based physical modelling [10,11], and numerical modelling [12]. Having used Singapore climate data, Rahardjo et al. [13] studied the effect of flux boundary conditions on pore water pressure variation in a slope. In contrast, Yunusa et al. [14] studied it with consideration of Malaysia climate. Zhang et al. [3] performed research on the effect of rainfall infiltration in a slope using Seep/w both for the steady-state and transient condition. The studied slope inclined 30° with a horizontal surface, and the soil has been considered isotropic and homogenous. The obtained results indicate that the matric suction is mainly affected by ground surface moisture flux. In transient condition rainfall flux, the saturated coefficient of permeability and water storage function showed a significant role in pore water pressure variation.

As mentioned earlier, many researchers have studied the influence of infiltration on slope stability, but most studies have been carried out on the natural slope. Thereby, it can be mentioned that the research studies on the rainfall-induced railway embankment slope instability are not sufficient in the available literature. However, some researches on railway embankment stability can be found in the literature [18-25]. Despite that, most of the available studies in the literature neglected the coupling effects of train load and rainfall water infiltration on the slope stability analysis. Therefore, the aim of this paper is to study the effect of rainfall infiltration and applied trainload on safety factors using Seep/W and Slope/W.

2. Theory

2.1. Water flow

The water flow calculation in the saturated soil is based on Darcy’s law, according to Equation 1.[3].

\[ v = -k \frac{\partial h}{\partial y} \]  

(1)

\( V \) is equivalent to flow rate or flux, illustrating the Darcian velocity, \( k \) is hydraulic conductivity, and \( \partial h/\partial y \) is hydraulic gradient. Equation 1 is based on constant hydraulic conductivity, which is one of the saturated soil features. Equation 1 can also be used for water velocity in the unsaturated condition, provided that the \( k \) should be considered as a function of matric suction. The flow of water in the soil for saturated and unsaturated conditions is different [16]. Equation 2 can be utilized for a transient flow of water through unsaturated soil [17].

\[ \frac{\partial}{\partial x} (k_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y} (k_y \frac{\partial h}{\partial y}) + Q = \frac{\partial \theta}{\partial t} \]  

(2)

Where \( h \) is the total hydraulic head, \( k \) is hydraulic conductivity, \( Q \) is the applied boundary flux, \( \theta \), is the volumetric water content and, \( t \) is time.

2.2. Factor of safety

In civil engineering projects analyzing of stability of slope is of paramount importance. For doing so, different methods such as the finite element method and limit equilibrium method can be utilized. In this research, the Morgenstern-Price method, which is based on the limit equilibrium theory, is used to
calculate the factor of safety. The moment equilibrium and force equilibrium are two factors that the limit equilibrium theory is based on [18]. Therefore in the saturated condition, Equation 3 and Equation 4 can be used for force and moment equilibrium safety factor, respectively [19]:

\[
F_f = \frac{\sum [c' \beta \cos \alpha + \{N - U_w \beta \} \tan \phi \cos \alpha]}{\sum N \sin \alpha} \\
F_m = \frac{\sum [c' \beta R + \{N - U_w \beta \} R \tan \phi]}{\sum W_x - \sum N_f}
\]  

(3)

(4)

Where, \(c'\), is the effective stress, \(\beta\), is the slope length at the bottom of the slice, \(\alpha\), is the inclination of slice base, \(N\), normal force at the bottom of the slice, \(U_w\), is pore water pressure, \(\phi\), effective friction angle, \(W_x\), is total slice weight, and \(R\), \(x\), \(f\), are geometric parameters.

In the same way, to consider the matrix suction effects on shear strength of soil, Equation 5 and Equation 6 are used for the safety factor calculations based on force and moment, respectively [19].

\[
F_f = \frac{\sum [c' \beta \cos \alpha + \{N - U_w \beta \frac{\tan \phi^b}{\tan \phi} \} \tan \phi \cos \alpha]}{\sum N \sin \alpha} \\
F_m = \frac{\sum [c' \beta R + \{N - U_w \beta \frac{\tan \phi^b}{\tan \phi} \} R \tan \phi]}{\sum W_x - \sum N_f}
\]  

(5)

(6)

Where, \(\phi^b\), is the angle that represents the share of matric suction in the shear strength.

3. Method and Materials

3.1. Laboratory experiments

In the current study, the soil used as embankment material was collected from Universiti Teknologi Malaysia, Johor Bahru. The coordinate of the selected site for soil sampling is 1°33'32.9"N 103°38'39.4"E. The collected samples were then tested in the laboratory. Based on the USCS system [20], the soil is classified as elastic silt or silty clay (MH), while based on the British Soil Classification System (BSCS), it is categorized as high plasticity sandy silt (MHS). Table 1 illustrates some basic and mechanical characteristics of subgrade, while Table 2 summarizes the used material’s hydraulic features. The soil-water characteristic curve of subgrade was obtained using the pressure plate extractor (i.e., axis translation) method [21]. However, the lab experiment data is a few obtained result points that cannot be used effectively for numerical modelling. In other words, the continuous soil water characteristics curve (SWCC) in the desired matric suction range is of importance in numerical modelling [22]. Thus, the fitting parameters were then generated using the SWRC-Fit software [36][37]. The result obtained from the pressure plate test used in SWRC-Fit software and the acquired graph illustrates good compatibility of test results with Van Genuchten (1980), Fredlund and Xing (1994), and Brooks and Corey (1964) fitting models, as shown in Figure 1. It should be noted that since the application of drying SWCC yields a lower factor of safety than wetting and combined SWCC [23], thus in this study, the considered SWCC is a drying pattern. Furthermore, the saturated hydraulic conductivity of the soil has been obtained using the falling head method. The unsaturated hydraulic conductivity was calculated with the indirect measurement method, using the SWCC and saturated hydraulic conductivity, as shown in Figure 2.
Table 1. Index and mechanical characteristics of subgrade

| Properties                        | Symbol | Value  |
|-----------------------------------|--------|--------|
| Liquid limit: %                   | \( l_l \) | 70.3   |
| Plastic limit: %                  | \( P_l \) | 42     |
| Plasticity index: %               | \( P_i \) | 28.3   |
| Gravel: %                         | -      | 12.79  |
| Sand: %                           | -      | 17.54  |
| Silt: %                           | -      | 61.26  |
| Clay: %                           | -      | 8.41   |
| Soil classification:              |        |        |
| USCS                              | -      | MH     |
| AASHTO                           | -      | A-7-5  |
| Optimum moisture content: %       | OMC    | 28     |
| Maximum dry density: g/cm\(^3\)   | MDD    | 1.39   |
| Specific gravity                  | \( G_s \) | 2.74   |
| Effective cohesion: KPa (Based on previous studies) | \( c' \) | 7.2 |
| Effective friction angle: ° (Based on previous studies) | \( \phi \) | 32 |
| Friction angle related to matric suction: | \( \phi^b \) | \( 2 / 3 \phi \) |
| Dry unit weight: KN/m\(^3\)       | \( \gamma \) | 13.64 |
| Poison ratio                      | \( \nu \) | 0.35   |

Table 2. Subgrade hydraulic characteristics

| Properties                                      | Value          |
|------------------------------------------------|----------------|
| Saturated hydraulic conductivity \( K_s \), (m/s) | \( 1.9 \times 10^{-8} \) |
| \( n \)                                        | 0.78           |
| \( m \)                                        | 1.87           |
| \( a \)                                        | 189.41         |
| Residual volumetric water content, \( \theta_r \) | 0.23           |
| Saturated volumetric water content, \( \theta_s \) | 0.54           |
Figure 1. Subgrade SWCC

Figure 2. Unsaturated hydraulic conductivity

The $\phi^b$ factor considering the influence of matric suction $(u_a - u_w)$ in shear strength of soil takes various values according to the degree of saturation. For instance, in the saturated condition, the
\( \phi^b = \phi \) [24] but for the unsaturated condition, it can take a value of \( 2/3\phi \) [14]. Therefore, in the current study, for unsaturated condition \( \phi^b \) value is considered as \( 2/3\phi \).

3.2. Rainfall Data

The rainfall data is the paramount importance in slope stability analysis to be considered. This issue's importance is doubled for tropical regions where the annual rainfall intensity is considerably high [10]. The frequent rainfall has caused many slope failures in tropical regions, including Malaysia [8]. The ponding does not occur when the rainfall intensity is low(i.e., the rapid ponding happens when the rainfall intensity is greater than 10mm/h) [6]. In other words, all the rainfall water can infiltrate if the saturated permeability is equal to or greater than the infiltration rate [25]. In this regard, Kassim et al. [26] conducted detailed research simulating the effect of different permeability values on negative pore water pressure. The obtained results depicted the ponding phenomena when the infiltration rate was more significant than saturated hydraulic conductivity (\( q > K_s \)) of the top layer (silty sand).

In the current research, the rainfall data obtained from the Department of Irrigation and Drainage of Malaysia for 2019 and 2020. The rainfall data used in this study have been recorded in the Senai metrology station, located in University Technology Malaysia. Figure 3 depicts the monthly rainfall of Johor Bahru based on the Senai metrology station. In Figure 3, it is seen that December has the maximum value rainfall of 403.5mm, while July month possesses 29.5 mm, which is the minimum value. Therefore, December and July months are selected in this research that Figure 4 depicts daily rainfall intensity for selected months. The whole throughfall does not percolate to the ground. Thus, the rainfall infiltration rate has been taken differently by researchers. For instance, Ng et al. [27] have considered 60% and 40% precipitation for infiltration and run-off, respectively, while Rahardjo et al. [28] have suggested 40-74% of total rainfall amount as infiltration value. However, in this study, 70% and 30% of rainfall are taken as infiltration and run-off value, respectively [29, 14].

![Figure 3. Monthly rainfall](image-url)
3.3. Numerical Modelling
Slopes can be categorized into two types, namely natural slope and human-made slope. Factors causing the slope failure can be varying, but most of the slope failure (i.e., 60%) caused by design errors [30]. Selection of unsuitable slope inclination and high (i.e., slope geometry) and incapability in finding the load and soil strength parameters are the most common design errors causing slope instability [31]. Therefore, the railway embankment slope must be planned and designed carefully and effectively in the early planning stages. In this study, the slope of the embankment is considered 1.5H:1V. For avoiding the dimension effects on numerical modelling, the dimensions of the geometry model are taken with respect to [16]. The applied load is considered for the maximum speed of 160km/h and axle load of 18.5ton. The details of track and train are illustrated in Table 3.

| Parameters          | Value                        |
|---------------------|------------------------------|
| Gauge               | 1435 mm                      |
| Axle load           | 18.5 ton (184.33kN)          |
| Speed               | 160 km/h                     |
| Dynamic impact factor| 1.54                        |
| Ballast thickness   | 0.4m                         |
| Sleeper: Length     | 2.6 m                        |
|                     | Width 0.3 m                  |
|                     | Height 0.224 m               |

For calculating the tangent pressure in the interface of sleeper and ballast, the applied load on rail and sleeper interface needs to be calculated. For doing so, Equation 7 can be used [32]. Afterward, Equation 8 is utilized to calculate the impact factor due to speed. Finally, Equation 9 is applied to compute the value of tangential stress on sleeper and ballast interface [33].

\[ q_r = 0.5IF \times P \]  
\[ IF = 1 + \frac{4.5V^2}{10^5} - \frac{1.5V^3}{10^6} \]  
\[ q_r = 0.5 \times IF \times P \]  
\[ IF = 1 + \frac{4.5V^2}{10^5} - \frac{1.5V^3}{10^6} \]
Where $q_r$ (kN) is applied load on the interface of rail and sleeper, $P$ (kN) represents the wheel load, $IF$ is the impact factor, $V$ (km/h), is design speed, $A$ is the contact area of sleeper with ballast, and $P_a$ (kPa), is the tangential stress on the interface of sleeper and ballast. Having considered the specifications of Table 1, the $P_a = 181.96$ kPa is obtained using Equation 9. Since the ballast layer is not considered in this modelling, the maximum applied stress on the surface of subgrade needs to be found due to 0.4m ballast thickness using Equation 10.

$$P_a = \frac{2q_r}{A}$$

(9)

$$P_c = \frac{0.17P_a}{h^{0.25}}$$

(10)

$P$ (kPa), represents the maximum stress on the top of the subgrade, while $h$ (m) shows the thickness of granular material on the top of the subgrade. Thus, the applied maximum stress on the top of the subgrade is acquired 97kPa based on the considered ballast thickness.

The flux boundary condition is considered on the ground surface (i.e., 8-7-6-5-4-3) to model the influence of rainfall on matric suction and safety factor. Besides, the water table's location is assumed 2m below the base of the embankment. Briefly, Figure 5 illustrates the flowchart of numerical modelling, and Figure 6 depicts embankment geometry. Section a-a in Figure 6 is illustrated to evaluate the matric suction change due to rainfall infiltration.

![Flowchart of numerical analysis](image-url)

**Figure 5.** Flowchart of numerical analysis
Although different methods are available in Seep/W for slope stability analysis, in this research, the Morgenstern-Price method that considers both moment equilibrium and force equilibrium have been applied in numerical modelling.

4. Results and Discussions
The safety factor decrease can be occurred due to reduced shear strength and increased shear stress. The strength decline can be caused by increasing moisture content and decreasing matric suction, while shear stress is caused by external factors such as applying load and traffic load. The rate of matric suction dissipation relates to rainfall intensity, rainfall duration, and soil permeability [3]. In regard to tropical regions' climate conditions, it can be stated that 80% of slope instability occurring in tropical regions is related to matric suction dissipation [34]. The shear strength reduction during the rainfall infiltration is caused by decreased matric suction along the potential slip surface [22]. This phenomenon can be clearly explained in section a-a of Figure 6 in Figure7. The negative pore-water pressure (Matric suction) exists above the water table before starting the rainfall, but the decreasing matric suction starts with rainfall. Besides, Figure 7b illustrates that during December, the decrement is more than that of July, as depicted in Figure 7a. This issue is attributed to rainfall intensity, which is higher in December compared with July.
Figure 7. Pore water pressure in section 1-1 a) for July b) for December

Moreover, depth and time are two parameters that govern pore water pressure [35]. As shown in Figure 7, at the beginning (hydrostatic condition), the pore water pressure is negative above the water table. Afterward, the matric suction decreases due to rainfall intensity over time. Besides, looking at Figure 7, it can be readily understood that the rate of change in negative pore water pressure due to rainfall is getting smaller with depth. Therefore, as shown in Figure 8, the factor of safety (FS) shows a decreasing pattern when the embankment is subjected to rainfall infiltration. Whereas Figure 9 depicts the influence of both rainfall infiltration and applied load on the safety factor reduction pattern. By comparing Figure 8 and Figure 9, it can be readily perceived that the applied load excessively diminished the factor of safety (FS) when incorporated with rainfall percolation. However, the rainfall alone reduces the safety factor. Nevertheless, its influence is not significant when both load and infiltration have been applied to the embankment together.

Figure 8. Influence of rainfall on factor of safety a) in July b) in December
Figure 9. Influence of rainfall and trainload on the factor of safety a) in July b) in December

Succinctly the influence of rainfall on safety factor can be attributed to the decreased shear strength due to positive excessive pore water pressure or decreasing matric suction, as can be seen in Figure 7. On the other hand, the applied load's influence on diminishing the safety factor can be ascribed to the increased shear stress. Figure 10 illustrates the slip surface location at the end of December, where the safety factor is 2.875 and 1.654 for unloading and loading conditions, respectively.

Figure 10. Slip surface at the end of December a) effect of rainfall b) effect of rainfall and load
5. Conclusions
This research has been conducted on the stability analysis of a presumed railway embankment. Based on the results obtained, the following conclusion can be drawn:

- The decreasing water content results in increasing matric suction.
- The permeability in the unsaturated condition is a matric suction function; the permeability decreases with increasing matric suction.
- The increasing positive pore water pressure or decreasing matric suction reduces the safety factor resulting in railway instability.
- The rainy seasons are more critical for railway embankment slope since the positive pore water pressure increases excessively in the rainy seasons.
- The decreasing level of matric suction depends on the depth where rainfall water can infiltrate, and beyond that depth, the matric suction does not change.
- The applied load on the railway track has a negative influence on railway embankment stability, and this influence becomes more intense with train operation during the rainy seasons.

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