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Optimizing Performance of Location for Horizontal and Chimney Drainage of Earthen Slopes Retaining Walls on Stability

B. Oghati Bakhshayesh, F. Salmasi*, S. Haji Azizi

Department of Water Engineering, Faculty of Agriculture, University of Tabriz, Tabriz, Iran

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ABSTRACT

Underground water levels and pore water pressure can be increased as a result of heavy rainfall which can lead failure of earthen slopes. Retaining walls are the most well-known structures in order to increase earthen slope stability. In this study, the stability of earthen slopes is numerically simulated in critical hydrological situations. The simulations included pore pressure behind the retaining walls which lead to instability. Among the investigated parameters were: precipitation intensity, soil type, position and the diameter of drainage passages. Both horizontal and chimney drainages were simulated for the study. For fine-grained soils with intensive precipitation, using a single horizontal drainage passageway could not maintain sufficient stability for the retaining wall. Precipitation could have severe impact on stability in which increase of 5 to 15 mm/h would increase pore pressure from 7.09 kN to 75.39 kN which is so dramatic change. For coarse-grained soils, a retaining wall provides stability with a single horizontal drainage pipe; the horizontal pipe is able to discharge all the excess water behind the retaining wall. A chimney drainage system provided the best results, and the stability of the retaining wall did not endanger, even under the worst circumstances. Linear and non-linear regression relations were produced in dimensionless form which are providing 0.97 for R^2 and 0.11 for RMSE values which implys the accurcy of equations. The accuracy of the regression determine their usage in practical applications.

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INTRODUCTION

While heavy precipitation occurs, there is an increase in the pore pressure of the soil in which poses a potential risk to the soil slopes, especially for fine-grained soils. Therefore, slopes which the risks of sliding can lead to high economic loss or loss of life, there is an obligation to build retaining walls. Retaining walls are usually used to restrain soil where the natural ground surface has a steep slope. The use of these structures is mostly accompanied by construction of roads and highways near abrupt ground surface slopes [1]. Even with retaining walls, there is a requirment for proper drainage and reduction of pore water pressure, especially when heavy rainfall or high groundwater levels occur frequently.

The stability of earthen slopes plays an important role in the daily life of human beings. Controlling slopes against erosion and sliding is important for roads, residential areas, dams, and etc. Groundwater levels can rise rapidly in case of heavy rainfalls, consiquently increasing the pore water pressure. This causes the shear strength of the soil to be decreased, and the risk of failure to be increased. So that drainage plays a vital role even with a strong retaining wall. For example, on July 23, 1994, a severe landslide occurred on the retaining wall of Kwun Lung Lau of Hong Kong after heavy rains, resulting death of five people [2]. To achieve adequate retaining wall drainage, various methods are applied, the most practical of which is the use of horizontal drains and chimney drains. The initial use of horizontal drains was in California. Stanton [3] reported on the successful use of horizontal drains for improving the stability of large slopes, and since then, historical cases had been published from many countries showing the effect of

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*Corresponding Author Email: farzin.salmasi@gmail.com (F. Salmasi)

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horizontal drains on the stability of slopes and embankments under different geological and hydrological conditions [4–10]. Au and Pang [11] studied the drainage system for removing percolated water and described a common pattern for water movement from horizontal drains. The results showed that the installation of an irregular drainage system (in different places and situations), surface water can be collected. Fishman [12] has studied the stability of soil slopes with concrete walls and their contact surface with rock bed. That study provided a discussion on mechanisms of sliding, overturning, and limited tilting. Fishman [12] showed that at the contact surface of the retaining wall with the substrate, sliding can occur when the shear parameters of the foundation are weakened. With partial and limited tilting or fracture in the retaining walls, this study has revealed that failure of the upper heel of the wall and excessive pore water pressure in this area is a main cause of failure. Kloukinas [13] investigated earthquakes on prefabricated block retaining walls. The results are in good agreement with theoretical models and give a better understanding of the complex performance of these factors. That study considered the effect of earthquakes and examined the stability of the wall against sliding. Blake et al. [14] modeled a retaining wall using the finite element method to predict excess pore water pressure followed by heavy rainfall; the effect of drains was also investigated in that study. They recommended use of horizontal drains to increase the interaction between the pore water pressure behind the retaining wall and the stability of the retaining wall. Moharrami et al. [15] investigated the effect of horizontal drains on the stability of earthen slopes with rapid draw down of a reservoir level. They suggested the use of drainage systems with lower upstream slopes and found that increasing the number of drains increases upstream slope stability. Rahardjo et al. [16] studied the optimal position of horizontal drains by considering two soil slopes. They concluded that with intense rainfall, the stability of the slopes cannot be examined using a steady state analysis. For subsurface slope, Pathmanathan [17] refers to positive effect of horizontal drains for slope stabilization. Shivakumar et al. [18] studied the stability of slopes using the finite element method and the need for investigating stability during rapid draw down from a reservoir. Viswanadham et al. [19] reported a 76-78% reduction in pore water pressure with chimney drainage in comparison to a retaining wall without a chimney drain. Boeckmann and Loher [20] suggested using weep holes instead of drainage in the design of retaining walls with earthen slopes. This drainage system are easy to maintain; they consist of two parts, a fixed part inside the retaining wall and a filter that is easy to repair and maintain.

Despite this prior research, there is a paucity of information on the design and implementation of retaining wall drainage systems, the requirment for design standards is undenyable. Also, the stability of the slopes which applied different types of drainage systems has not been studied, and no comparisons have been made between the results obtained from different types of drainage. Hence, the performance of horizontal and chimney drains in controlling pore water pressure and the stability of soil slopes during heavy rains are studied using two software programs, SEEP/W and SLOPE/W [21]. First, the desired soil slope is modeled in SEEP/W software, then by defining the available materials and boundary conditions, the pore water pressure are determined. The results are entered into the SLOPE/W software and then the effect of using horizontal and chimney drains on slope stability during heavy rainfall was investigated. Finally, regression relations was presented to enhance the calculation of forces and overturning torque on the retaining wall.

MATERIAL AND METHODS

SEEP/W software

SEEP/W software is a part of GEO-STUDIO package. This software is based on the Finite Element Method (FEM) and allows the user to model the seepage and distribution of pore water pressure in porous media. In addition to simulating flow in saturated environments, this software is also able to model flow in an unsaturated medium which is a substantial advantage in practical modeling of groundwater flows in aquifers [22]. SEEP/W software has been used broadly in various studies. For example, Khalili Shayan and Amiri Tokaldany [23] compared the leakage and uplift pressure values obtained from the SEEP/W with an experiment and the comparison indicated a robust ability of that for such calculations. In addition, the US Bureau Reclamation (USBR) conducted a series of studies in 2014 using SEEP/W and reported high accuracy from the software [24].

SLOPE/W software

SLOPE/W software is also a part of GEO-STUDIO package and is used to check sloping surfaces and to determine the safety factor of earthen slopes. Unlike other parts of the GEO-STUDIO software, SLOPE/W does not use the finite element method, it relies upon drawing methods for slope stability analysis [25]. SLOPE/W software uses the Generalized Limit Equilibrium (GLE) method that is based on an equilibrium analysis of forces or moments. Prior studies, such as Janbu, Spenser, Bishop and etc. have been completed with this approach. Figure 1 shows the hypothetical retaining wall in this study. The two types of drainage systems are: chimney and horizontal drains. The studied parameters are also specified in Table 1.

While several parameters play a role in the stability of the retaining wall, it is not possible to study all of them

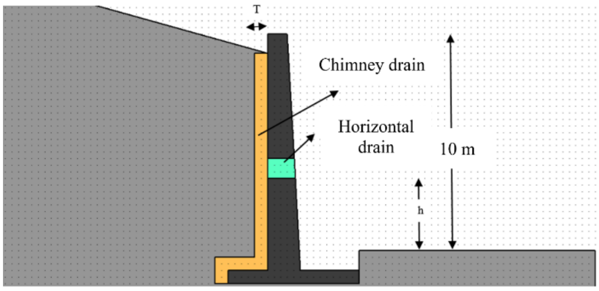


Figure 1. Retaining wall with a height of 10m including a chimney and a horizontal drainage system

simultaneously. The most important parameters in this study consisting drainage pipe height, the intensity of precipitation, thickness of the drainage filter layer (for chimney drainage) and the soil type behind the retaining wall. Parameters such as the retaining wall height, retaining wall thickness, wall foundation shape, bedrock position, retaining wall material, and soil slope behind the retaining wall are considered to be constant. Table 1 shows the values of the parameters used in the models. In this study, to achieve a result that can be used in practical applications, three different soil types are used, the characteristics of which are shown in Table 2.

Reducing the size of the computational elements will increase the accuracy of the calculations. To explore the impact of element size, a mesh-independence study was performed by Hasani et al. [27]. To determine the appropriate number of elements, simulations were performed with increasingly smaller elements until the results no longer depended on the elements [34]. As an outcome of this study, 44,716 elements were found to provide independent results. In these models, an unsteady simulation was performed because the precipitation rate was time-varying. The transient simulations incorporated 100 time steps that spanned two days of simulation. Precipitations amounts of 240mm and 720mm were considered. The boundary conditions were zero pressure at the drainage outlet, a prescribed rainfall intensity at the inlet. The drains and retaining walls are defined as materials with different permeability.

Table 1. Values of parameters used in simulated models

Effective parameters	**Values**
Distance of horizontal drain from retaining wall invert (*h*)	0, 2, 4, 6 and 8 m
Thickness of chimney drain (*T*)	10, 20, 30, 40 and 50 cm
Precipitation intensity (*P*)	5 and 15 mm/h

Table 2. Geotechnical characteristic of soils [26, 28–34]

Parameters	**Silt**	**Silty loam**	**Clay**
K_{sat} (*m/s*)	$5.052*10^{-6}$	$2.107*10^{-6}$	$1.712*10^{-6}$
K_x/K_y	1	1	1
Saturated water content	0.45	0.49	0.51
Residual water content	0.09	0.1	0.11
Sliding criteria	Mohr-coulomb	Mohr-coulomb	Mohr-coulomb
Specific unit weight (kN/m^3)	18.24	18.43	18.86
ϕ (*Deg.*)	29	25.3	23.1
Cohesiveness (*kPa*)	3.4	5	7.8

Derivation of destructive force and overturning moment through pore water pressure

Since SEEP/W software cannot calculate the forces or the overturning moment on the retaining wall, an alternative approach must be used. Equation (1) is used to relate the pressure to the force on the retaining wall.

$$F = P * A \tag{1}$$

where P is the pore water pressure, F is the exerted force, and A is the surface area. The pore water pressure is an output from the numerical simulation and is determined at each individual element. The sum of the forces on the individual elements provides the total force on the wall, as indicated by Equation (2).

$$F_i = \frac{P_i + P_{i-1}}{2} \times (y_i - y_{i-1}) \tag{2}$$

In Equation (2), P_i is the pore water pressure on element i and P_{i-1} is the pore water pressure on the adjacent element. To analyze the relationship between force and position of the drain or drain diameter, these values are defined by two dimensionless parameters: h/H and T/H, where H is the height of the retaining wall (H=10 m). The symbol h is the distance of horizontal drainage or pipe from the floor of the retaining wall and takes on values of 0, 2, 4, 6 and 8 m. Lastly, T is the diameter of the drainage filter in the chimney and has values of 10, 20, 30, 40 and 50 cm. In addition, the dimensionless parameter F/W is used in this study, where F is the force on the wall and W is the weight of the retaining wall.

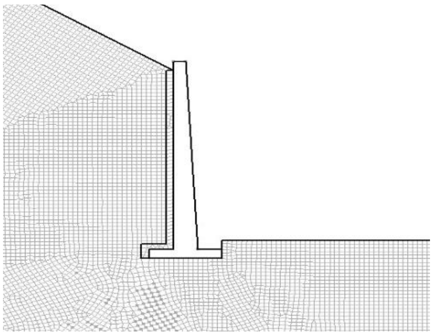
The weight of the retaining wall (W) is calculated using reinforced concrete. The specific weight of the reinforced concrete (ρ) is 2.6 ton/m^3. The destructive torque in this model is the torque on the retaining wall from pore water pressure. The torque is related to the weight of the retaining wall and depends on the shape and the materials used to construct the wall. The torque axis is the toe (downstream) of the retaining wall.

The force exerted on each element is multiplied by its average vertical distance from the torque axis. The sum of all such products is equal to the overturning torque. The stability torque is defined as the torque exerted by the weight of each element in the retaining wall, above the same axis. The dimensionless ratio of torque/moment is the ratio between the destructive torque and the stability/resistance torque, i.e. M_d/M_r.

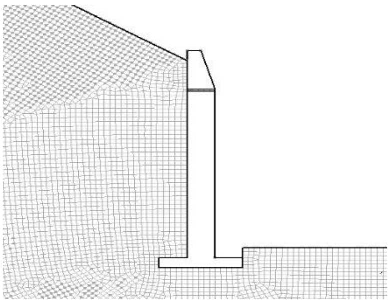
Regarding the intensity of precipitation and the hydraulic conductivity of the soil, the governing dimensionless relationship is P/K, where P is the intensity of precipitation (mm/h) and K is the hydraulic conductivity of the soil (mm/h).

In addition, the diameter of horizontal drainage pipes in this study is assumed to be 10 cm. In the following, two-dimensional regression relations are presented for estimating the force and torque acting on a retaining wall. Figure 2 shows an example of a simulated retaining wall model with two types of drainage systems.

As mentioned earlier, an unsteady simulation was performed because of the transient effects of rainfall. In order to use results from the unsteady simulation, the initial soil pore water pressure or the groundwater level must be specified. Initial conditions can be obtained through a steady state calculation with boundary conditions that are long-term averages of precipitation. Parameters such as the texture of each soil layer, the precipitation level, the duration and average precipitation, surface evaporation, slope, bed type, and impermeable layer depth have a major impact on the groundwater surface. In order to model each situation accurately, each model will have its own geotechnical conditions; not all conditions can be generalized to a general situation.



(a): Retaining wall model with a chimney drain and filter diameter of 30 cm and the computational elements



(b): Retaining wall model with a horizontal drainage at a height of 8 m from the invert and the computational elements

Figure 2. The mesh near the retaining wall

The initial soil conditions were saturated and modeling was performed based on the most critical condition. Thus, the results obtained from this modeling are conservative with respect to actual conditions. The main purpose of this study is to utilize the above-described simulations and to compare and optimize the proper position and diameter of the drainage filter. Precipitation with a prescribed intensity were applied to the soil slope. Then, the stability of the slope was calculated. By examining the status of the model in terms of stability using both types of drainage (chimney and horizontal) and by changing their effective parameters, an attempt was made to identify an optimal drainage system to stabilize the soil slope in heavy rainfall. Next, regression relationships are presented to enable predictions of optimal drains and stability for any soil type.

RESULTS AND DISCUSSION

Figure 3 shows a view of retaining wall's initial conditions and the earthen slope in the SEEP/W software program before precipitation. Figure 4 shows the same conditions in SLOPE/W. Apllying zero rain, the slope is stable; after applying rain to this model, impacts to the slope stability will be evident.

The SLOPE/W software was originally developed to analyze the stability of slopes and rupturing of soil

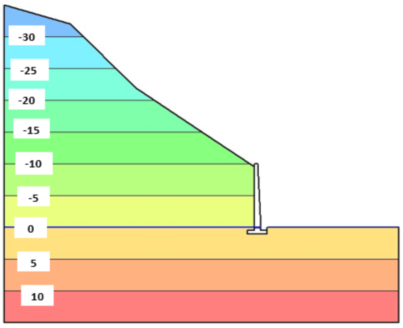


Figure 3. Initial pressure conditions for the horizontal drainage model, at a distance of zero meters from the bed

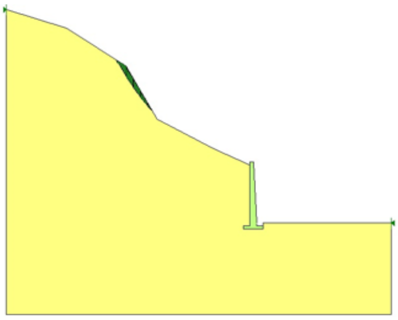


Figure 4. View of the slope failure with horizontal drainage at a distance of zero meters from the floor, before precipitation

slopes. The software can also calculate the factor of safety of soil slopes. However, in this model, the protective structure of the earthen slope is the retaining wall, and the stability of the slope is provided by the wall. The software does not have the capability of computing wall stability in cases of overturning or sliding, consequently a different approach is necessary. After the SLOPE/W software is used to compare the stability of the slope with and without a retaining wall, the stability of the wall itself is determined by an alternative method that utilizes the pore water pressure within the soil, behind the retaining wall.

Figure 5 shows a sliding region after rainfall and without a drainage system; Figure 6 also corresponds to the same slope but includes a drainage system. Comparison of these two numerical simulations shows that a drainage system reduces the region of sliding. This increases the safety factor of the slope against failure and has positive effect reducing the cost of construction.

According to Figure 5, after the rain, the slope has experienced significant slipping. If this slope were in a sensitive area, such as adjacent to roads or other structures, those objects would be damaged. The green portion of Figure 5 indicates soil rupture and there is a possibility of wall collapse. As Figure 6 shows, the use of a retaining wall and horizontal drainage has significantly improved slipping and wall stability. Therefore, choosing and optimizing the drainage can provide magnificent improvements to the system.

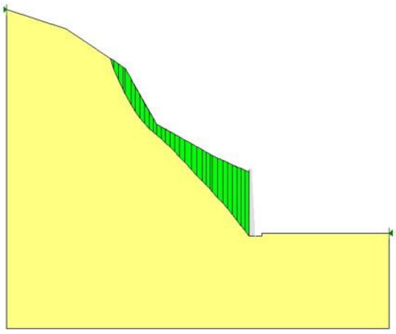


Figure 5. Sliding circle after rainfall without a drainage system

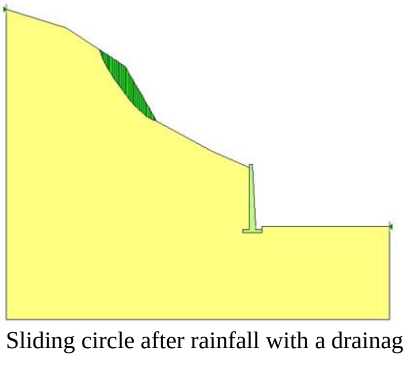


Figure 6. Sliding circle after rainfall with a drainage system

The effect of rainfall on increasing the pore water pressure of soil slope behind the retaining wall

The main factor that can increase the pore water pressure in the soil is the rate of precipitation. This is true both with seasonal and unpredictable precipitation in which drainage performance plays a decisive role. Figures 7 and 8 show examples of the effect of different rainfall intensities (5 and 15 mm/h) on the pore water pressure (unsteady simulation).

The two simulated models in Figures 7 and 8 are related to earthen slopes formed from clay material. The distance of horizontal drainage from the wall invert is zero meters. In the first model (Figue 7), the intensity of rainfall is to 5 mm per hour and after two consecutive days of rainfall, the force applied to the retaining wall is 7.09 kN. In the second model (Figure 8), after a sustained rainfall of 15 mm per hour, the force on the retaining wall is 75.39 kN, more than ten times increase. The overturning moment for the retaining wall in Figure 7 is calculated to be 18.60 kN-m for precipitation of 5 mm/h. The ratio of the resistant moment to the overturning moment is 19.27, which is quite stable. In the model where precipitation of 15 mm/h occurs (Figure 8), a very large overturning moment (M_o) results (M_o=414.73 kN-m). The ratio of the resistant moment to the overturning moment is 0.86 which is unstable and will inevitably lead to overturning, slipping, or breaking the wall.

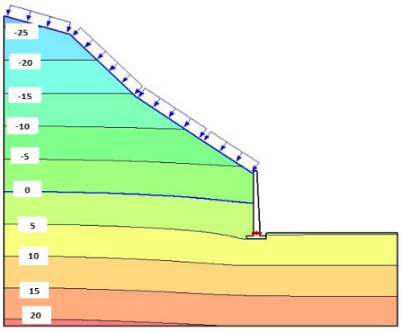


Figure 7. Contours of pore water pressure at 5 mm/h rainfall intensity (numbers are in meters)

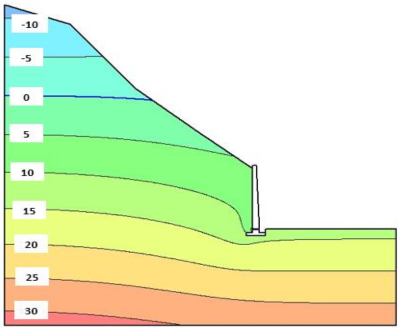


Figure 8. Contours of pressure at 15 mm/h rainfall intensity (numbers are in meters)

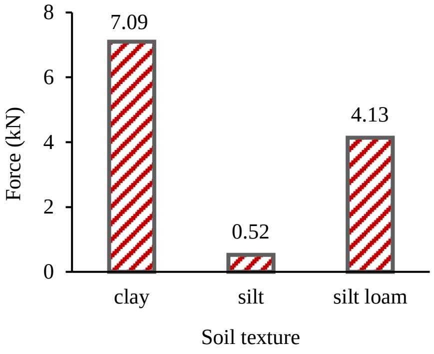
The effect of soil type behind the retaining wall on the pore water pressure and overturning moment

To understand the importance and effect of soil material on the stability of slopes by the retaining wall, the previous model, i.e. installation of drainage in the wall floor with a precipitation rate of 5 mm per hour was used. The results are provided in Figures 9-a. and 9-b for force and torque, respectively. Because the permeability or hydraulic conductivity of silt is higher than the other two types (silt loam and clay), it has a higher water seepage capacity and thus lower pore water pressures.

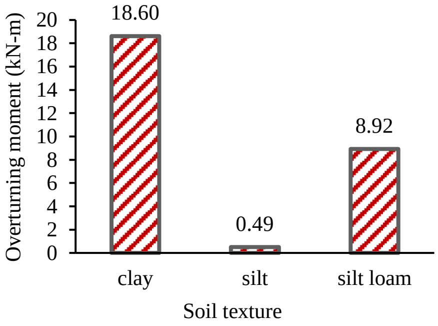
The effect of different drainage positions

The effect of horizontal drainage position on pore water pressure and stability of the retaining wall is investigated. It is noteworthy that in this model, only one drain is used. In fact, more than one drain can be placed in the retaining wall for improved results. Figure 10 shows the changes in force on the retaining wall for different positions. The results correspond to a precipitation rate of 5 mm per hour and with clay material on the slope behind the retaining wall.

From Figure 10, it can be concluded that the construction of drainage at lower positions has a better performance compared to the construction of drainage at higher positions. Water can only drain downwards through the soil, so that when the drainage location is elevated, any water beneath the drainage location is unaffected. Below the location of the drain, water accumulates and the resulting water pressure in the pores can endanger the stability of the soil slope. However, if several drains are used, the situation will be different and the distance between the drains as well as their location are important.



(a): Effect of soil texture on force



(b): Overturning moment for a precipitation rate of 5 mm/h and drainage in the floor of the retaining wall

Figure 9. Effect of soil texture on force and overturning moment

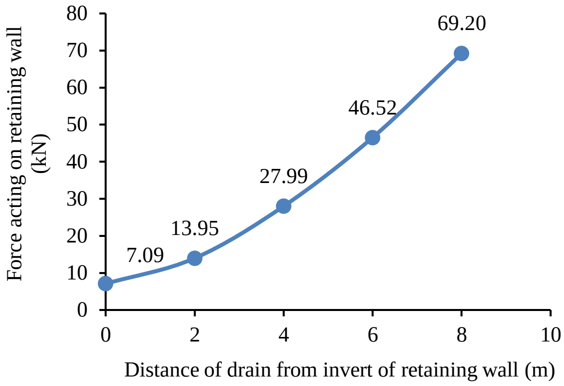


Figure 10. Effect of horizontal drainage position on the force applied to the retaining wall for a precipitation rate of 5 mm/h

General results obtained for force applied on the retaining wall and the derivation of regression equations

Regression equations were tested for their ability to predict the force applied to the retaining wall. The linear relationships presented for all three soil in Table 3.

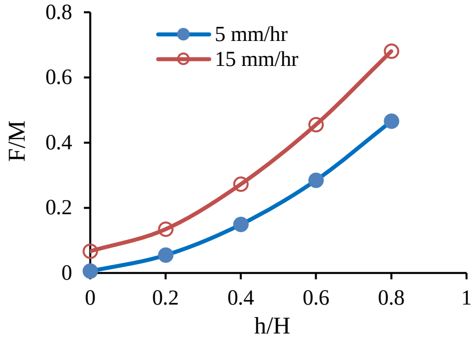
From the regression equations obtained from clay and silt loam soils, it is concluded that the regression equations are very similar and differ only in the thousandth digits of the coefficients. In terms of estimation error, the equation obtained from modeling with silt soil has a lower value than the others, but in terms of R^2, the third equation, which is related to silt loam soil, has a higher value. Since the hydraulic conductivity in these equations is also defined as a dimensionless parameter (*P/K*), these equations can be

Table 3. Linear regression relations for calculating the force on the wall for all three soil types

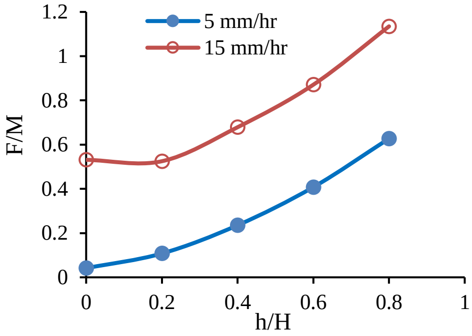
Soil type	Presented equations	R^2	R	RMSE	EF
Clay	$\frac{F}{M} = -0.273 + 0.756\frac{h}{H} + 0.37\frac{P}{K}$	0.966	0.98	0.06	0.96
Silt	$\frac{F}{M} = -0.143 + 0.675\frac{h}{H} + 0.236\frac{P}{K}$	0.944	0.97	0.04	0.94
Silt Loam	$\frac{F}{M} = -0.251 + 0.756\frac{h}{H} + 0.352\frac{P}{K}$	0.967	0.98	0.05	0.96

used in any type of soil and acceptable results can be expected. It should be noted that in obtaining these relationships, the results are provided in dimensionless variables as follows: *h/H* is the ratio of the height of the horizontal drain to the height of the retaining wall, *P/K* is the ratio of rainfall intensity to the hydraulic conductivity and the forces themselves are also relative. The horizontal force applied to the wall is about 100 kN (assuming a specific gravity of 2.6 ton/m^3 for reinforced concrete, which is an average of 2.5 to 2.7 ton/m^3).

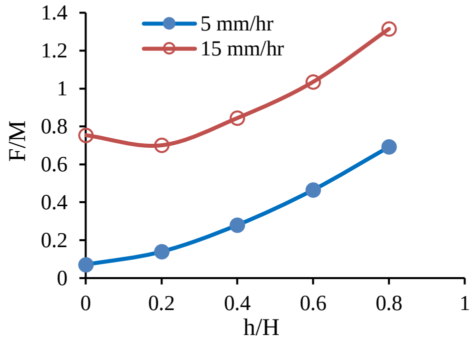
Graphs of the force acting on the retaining wall are presented in Figures 11-a, 11-b and 11-c for all types of soil. For clay and silt loam soils, a considerable observation is that with 15 mm/h of precipitation, a drainage position 2m from the toe of retaining wall provides better results for reducing the pore water pressure in the area behind the retaining wall. This does not applies for precipitation rate of 5 mm/h, meanwhile the best results for drain location would be at a distance of zero meters from the toe of retaining wall.



(a): Silt soil



(b): Silt loam soil



(c): Clay soil

Figure 11. Variation of relative force on a retaining wall with relative depth of a drain for three types of soils

Another noteworthy result is that for silt soil, the difference in pore water pressure with respect to different precipitation rates is less than the other two types of soils. Therefore, it can be concluded that with coarser soils, the variation in force with precipitation intensity is less than fine-grained soils. Of course, fine soils need more time to saturate and create positive pore water pressures, simiarly requiring more time to drain excess water.

Derivation of regression equations for moment ratio

A similar modeling approach is used for the overturning torque. First, the input data was converted to dimensionless format and then linear regression equations were generated. Table 4 lists the resulting regression equations for the respective soils.

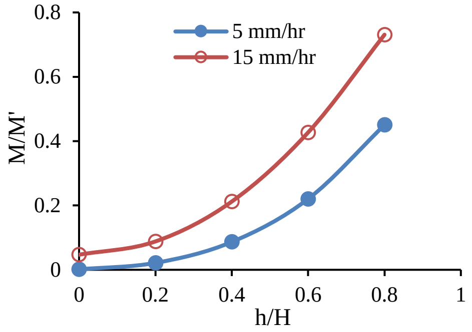
In Table 4, the relationships are very similar and similar results can be expected. In terms of coefficient values, these equations are very similar to the linear regression equations for force on the retaining wall. The effective parameters for determining torque are the force on the wall, the weight of the wall itself and the center of gravity. As a prediction for accuracy, the regression relationship for silt loam soil would provide better accuracy than the others in terms of R^2. It also has a lower RMSE, which is indicating the accuracy. Dimensionless diagrams are generated, as shown in Figure 12, for the torque results.

As seen in the figures, the moment increases substantially with more intense precipitation. Also, they generally increase with larger relative depth similar to the precipitation rates, there can be a relative minimum value.

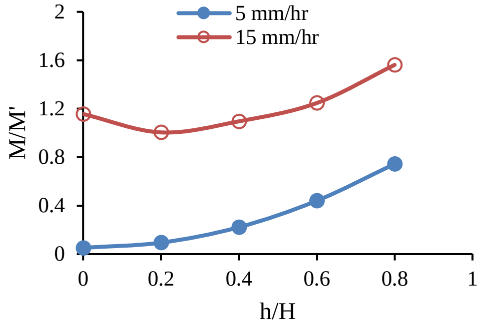
Coarser grain soils results are more sensitive than the other types of soils to precipitation rate. Using retaining walls for coarse soils, would result in reduction of the pore pressure and an increase in excess water discharge capacity. The more-coarse soils, will definitely lead to a more stable situation.

Table 4. Linear regression equations derived from torques rates analysis

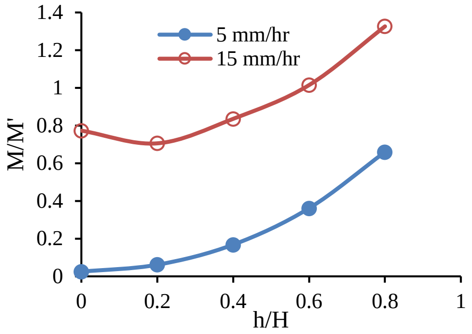
Soil type	**Presented equations**	**R^2**	**R**	**RMSE**	**EF**
Clay	$\frac{M}{\acute{M}} = -0.419 + 0.696\frac{h}{H} + 0.556\frac{P}{K}$	0.95	0.97	0.11	0.95
Silt	$\frac{M}{\acute{M}} = -0.197 + 0.701\frac{h}{H} + 0.264\frac{P}{K}$	0.87	0.93	0.07	0.87
Silt Loam	$\frac{M}{\acute{M}} = -0.381 + 0.746\frac{h}{H} + 0.513\frac{P}{K}$	0.95	0.97	0.08	0.95



(a): Silt soil



(b): Silt loam soil



(c): Clay soil

Figure 12. Variation of relative momentum on the retaining wall with relative depth of the drain for three types of soils

CONCLUSION

The use of chimney drainage with a filter and various materials has better impact on reducing pore water pressure. However implementing this type of drainage is costly and difficult. Horizontal or vertical pipe drainage systems application for slopes with coarse-grained soils, would reduced tensions on the retaining wall unlike non-drained and fine-grained soils slopes. The proposed linear regression equations are able to estimate the forces and the overturning torque. Retaining walls which restraining unsaturated soil slopes are more stable. However, in case the porous medium behind the retaining wall is saturated, the situation changes and the need for drainage becomes more vital. Another important recommendation for fine-grained soils slopes is that the use of multiple drainages for specific length in condition such heavy precipitation will lower the risk of the system faliure.

CONFLICT OF INTEREST

There is no conflict of interest

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Persian Abstract

چکیده

سطح آب زیرزمینی و فشار آب منفذی، می‌تواند با بارندگی شدید افزایش یافته و باعث تخریب شیب‌های خاکی گردد. دیوارهای حایل سازه‌های رایجی هستند که برای افزایش پایداری شیب‌های خاکی مورد استفاده قرار می‌گیرند. در مطالعه حاضر، پایداری شیب‌های خاکی در شرایط هیدرولوژیکی بحرانی به صورت عددی شبیه‌سازی گردیده است. شبیه‌سازی‌ها شامل فشار منفذی پشت دیوارهای حایل که موجب ناپایداری می‌شود، بود. دیگر پارامترهای مورد بررسی عبارتند از: شدت بارش، نوع خاک، موقعیت و قطر زهکش. همچنین هر دو نوع زهکش افقی و دودکشی مورد استفاده قرار گرفت. نتایج نشان داد که برای خاک‌های ریزدانه با بارش شدید، استفاده از یک زهکش افقی نمی‌تواند پایداری کافی برای دیوار حایل ایجاد کند. در حالیکه برای خاک‌های درشت دانه پایداری دیوار حایل به وسیله یک زهکش افقی قابل تامین است. این زهکش افقی می‌تواند تمام آب اضافی پشت دیوار حایل را تخلیه نماید. سیستم زهکش دودکشی بهترین نتیجه را به همراه داشت و پایداری دیوار حایل حتی در بدترین شرایط با هیچ خطری مواجه نبود. با توجه به گشتاور واژگونی و فشار منفذی آب پشت دیوار، روابط رگرسیون خطی و غیرخطی به صورت بدون بعد ارایه گردید. دقت این روابط رگرسیونی استفاده از آنها را در موارد عملی ممکن می‌سازد.