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Three-Dimensional Finite Element Analysis for Soil Slopes Stabilization using Piles

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ملخص البحث:

تدعيم الميول بأستخدام الخوازيق هي واحدة من الأساليب المستخدمة على نطاق واسع في العقود الأربعة الماضية. في هذا البحث يتم دراسة تأثير تثبيت الخوازيق في الميول على معامل الأمان و طبيعة الأنهيار. كما تم التحقق من نموذج العناصر المحددة ثلاثي الأبعاد من خلال نموذج تجريبي معملى تم إعداده في جامعة ميسوري - كولومبيا (2009). وتم تطوير نموذج ثلاثي الأبعاد باستخدام plaxis 3D V20 ، وكانت الطريقة التحليلية هي طريقة تقليل قوة القص. ثم أجريت دراسة لمعاملات مختلفة لتحديد تأثير موقع تثبيت الخوازيق، والميل، والطول، والتوزيع، وقطر الخازوق. وكذلك دراسة تأثير المسافات بين الخوازيق على معامل الأمان للميول ومقارنتها مع النتائج في الأبحاث السابقة. و أظهرت نتائج الدراسة أن الموقع الأمثل للخوازيق هو في منتصف الميل او اعلي قليلا. و إن التباعد بين الخوازيق له تأثير طفيف على معامل الأمان عندما كانت الخوازيق بالقرب من قمة أو قاع الميل. تظهرالخوازيق العمودية تحسنا في استقرار المنحدر من تلك التي يتم وضعها في الاتجاه العامودي إلى الميول.

***الكلمات الدلالية*: التحليل العددى، الخوازيق، ثبات الميول،معامل الأمان، موقع الخوازيق، أتجاه الخوازيق.**

ABSTRACT:

Using piles in stabilizing slopes is one of the widely used methods in the last four decades. In this paper the effect of installing piles in the slope on the safety factor and the shape of failure are studied. Three-dimensional finite element model was verified with a large -scale experimental model made at the University of Missouri-Columbia (2009). The three-dimensional model was established using plaxis 3D V20, and the analytical method was the shear strength reduction method. A parametric study was then conducted to identify the effect of the pile's position, inclination, length, configuration, and diameter. Also, the spacing between the pile on the slope's safety was studied and compared with the results in the literature. It is found that the optimum pile's position is in the middle of the slope or slightly upper. However, the spacing between the piles has a minor effect on the safety factor, mostly when the piles were near the slope's crest or toe. Vertical piles show improvement in the slope stability more than those placed in normal-direction to the slope.

Keywords: numerical analysis, pile, slope stability, factor of safety, pile position, pile direction.

1- INTRODUCTION

Various construction activities require analysing earth slopes' safety, such as highways, railway tracks, canals, mining, earth dams, and excavations for foundations' construction. Slope failure is considered as a movement in a part of the soil in the slope outward or downward. The failure occurs almost every way, gradually or unexpectedly, and with or without any obvious inducement. It mainly takes place when the driving force exceeds the resisting force along the plane of failure. There are many modes of failure, such as rotational, planner, and wedge failure. Stabilizing the earth slopes could be achieved using different methods, including removal and protection methods, drainage water, and reinforcement using geotextiles, nails, pitching, and piles. Stabilizing the earth slopes using pile has proven successful and effective in many situations in the past, because installing the piles is easy and doesn't affect the slope's equilibrium (DeBeer and Wallays 1970; Ito et al. 1981; Nethero 1982). Several approaches were conducted to get the most effective diameter, length, numbers, and piles' location through numerical and experimental analysis.

The limit equilibrium method deals with the pile as a supporting element. The piles add additional resistance to the slope while the interaction between the pile and the soil is neglected. Ito et al. (1975) submitted an equation to calculate the pile's reaction assuming that the pile is plastic deforming ground. Also, Hassiotis et al. (1997) used Ito's equation and friction circle method and found that the best pile's position to give a maximum safety factor is to be in the middle or slightly upper of the slope. Yamagami et al. (2000) used (Bishop method) and considered that the slope has two different slip surfaces in the upslope (AD) and downslope (BE) soil masses of the pile row as shown in Figure 1.

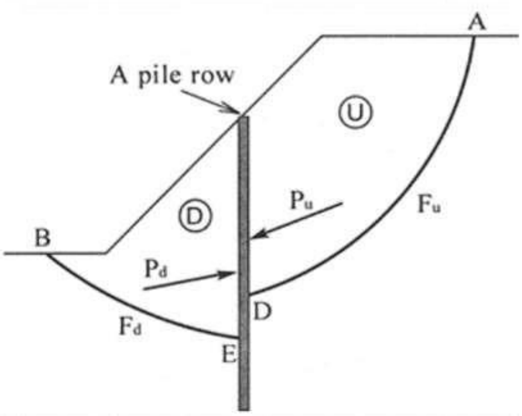


Figure 1 Basic Concept of Yamagami et al.' method (2000)

They determined two safety factors for the upslope and downslope sliding masses (Fu and Fd), the piles must at least provide a resistance force (Pd) corresponding to the two effects' net difference. Lee et al. (1995) used the uncoupled method in the analysis. The stability of the slope and the pile's response are treated individually. The piles are assumed to form a barrier and translate the load from the sliding soil mass to a more stable layer under the failure surface. For the slope stability, the conventional Bishop simplified method of slip circle analysis is adopted to determine the critical sliding surface, resisting moment, and overturning moment and get the factor of safety.

On the other hand, finite element method divides the model into meshes, and constitutive models is used to simulate the soil mass to calculate the stresses and the strains. Failure occurs in the soil when shear strength couldn't resist the applied shear stresses. Eventually, a reduction factor can be calculated for finite element methods using the 'c-φ reduction' procedure. In this approach, the strength of the soil is reduced incrementally until the slope fails. The shear strength reduction technique enables the user of the finite element method to calculate the factor of safety (reduction factor) for the slopes, Memon (2018).

Fei Cai and Keizo (2000) studied the effect of slope stabilization with piles on the safety factor using the three-dimension elasto-plastic shear strength reduction method and compared it with the results obtained from Bishop's simplified method. They found that, the safety factor resulting from the shear strength reduction method and the Bishop's simplified method is almost close.

Many researchers aim to study the piled or un-piled slop's behavior through experimental models like large scale model or centrifuge test. In the laboratory, Hajiazizi et al. (2007) use sandy soil to make a slope and then gradually loaded it using precipitation. Different types of soil slopes were examined, and the pile's position effect on the factor of safety was investigated.

This paper presents a numerical analysis that is performed using the finite element method to investigate the effect of installing piles in the slopes on the slope's safety, and changing the pile's parameter to get the maximum safety factor. First, the 3D numerical model was conducted using plaxis 3D V20, and it was verified with a large-scale experimental model. The numerical model is then used in a parametric study to observe the effect of the pile's length, position, diameter, and arrangement on the factor of safety.

2- CASE STUDY

Bozok (2009) made a large-scale model for a slope stabilized with micro piles to monitor the slope's failure mechanism by incrementally increasing the slope angle and evaluating the load transfer in the micro piles. He used a container to build the slope, a lifting mechanism to control the model's inclination, a water delivery system to control pore water pressures, and an instrumentation system, as shown in Figure 2. Two piles with 0.038m diameter and 0.75 m length were installed perpendicular to the slope face without a capping beam for the test; the pile consists of a steel tube filled with grout. The tube's diameter is 0.019m with a thickness of 2.4mm, and the soil was silty sand from the Missouri River. The spacing between the piles was 0.762m. The model failed at a slope inclination of 40 degrees.

Figure 2 Large-scale model of the slope (Bozok, 2009)

The height of the slope =1.50 m with plan 4.26 mx2.25 m, the slope is supported with two piles with free head, diameter=0.038m, Length=0.75m, the spacing between the piles was 0.762, and the model slope inclination is 24°, as shown in Figure 3.

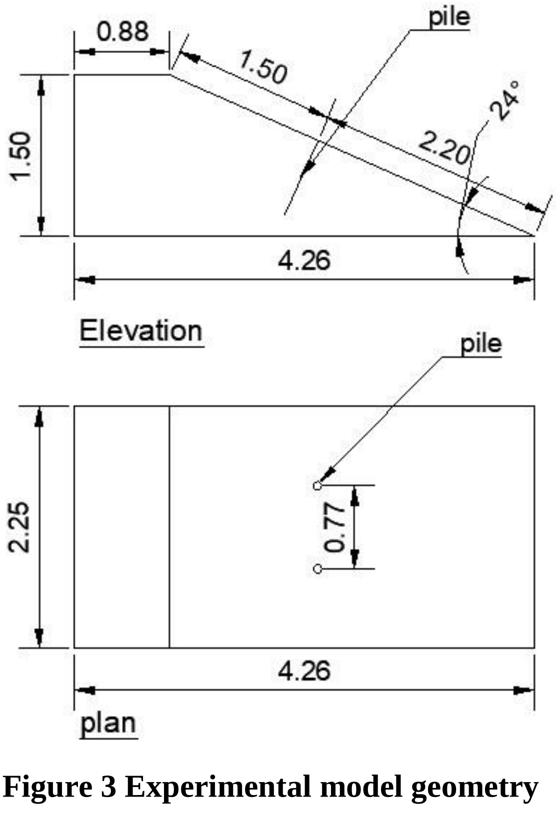


Figure 3 Experimental model geometry

silty sand soil from the Missouri River was used in the experiment. Several index tests were conducted in the University of Missouri Columbia geotechnical engineering lab to classify the soil. Two micro piles were used as a reinforcement element.

2.1- NUMERICAL MODELING

Figure (4) shows the numerical idealization of the experimental model by Bozok (2009) in order to validate the accuracy of the model to implement in the proposed parametric study

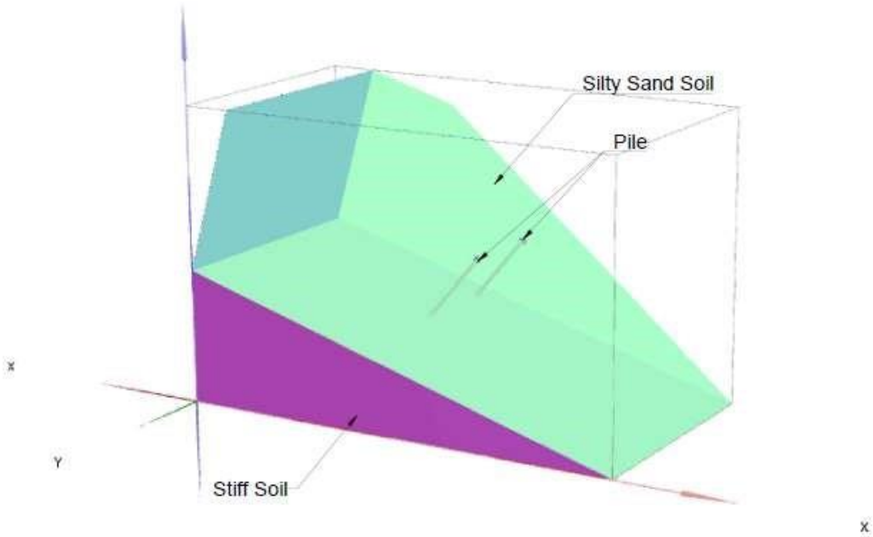
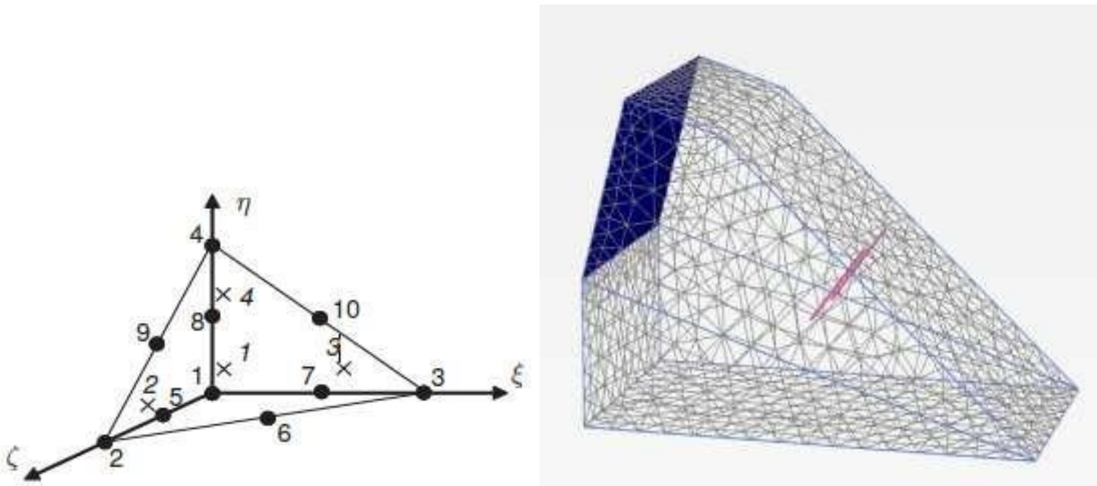


Figure 4 The 3D numerical model.

The 3D finite element mesh's basic soil element is 10-node tetrahedral mesh elements, and for the beam element, 3-nodes elements are used as shown in Figure 5. The model is normally fixed in the boundary Xmin, Xmax, Ymin, and Ymax, although Zmin is fully fixed and Zmax is free.



(a) (b)

Figure 5 (a) 10-nodes element and (b) Model's mesh

2.2- MATERIAL PARAMETERS

Table (1) shows the Mohr-Coulomb material models parameters of the silty sand soil used in the model and the stiff soil which represents the container used in the experiment, while table (2) shows the elastic parameters of the micro piles. **Table (1) Mohr-Coulomb Model Parameters**

Parameters	Unit	Silty sand	Stiff material
Modulus of elasticity	kN/m^2	34000	3000000
Poisson's ratio	---	0.25	0.23
Maximum dry unit weight	kN/m^3	18	30
Drained angle of internal friction Ø	Degree	33°	33°
Effective stress cohesion C	kN/m^2	3.4	1000
Constitutive model	---	Mohr-coulomb	Mohr-coulomb
Drainage type	---	Drained	Drained
Interface	----	Rigid	Rigid

Table (2) Elastic Parameters of Micro Piles

Parameters	Unit	Micro Pile
Modulus of elasticity	kN/m^2	$2x10^8$
Unit Weight	kN/m^3	76.9
Diameter	m	0.038 (grout and steel)
Length	m	0.75
Constitutive model	---	Linear-elastic
Inclination	---	Perpendicular to slope surface= 40°

2.3- STRENGTH REDUCTION METHOD (SRM)

Using the SRM in finite element method is not only dealing with the interaction between the soil and the pile but also calculating the safety factor of the slopes. For slopes, the factor of safety is defined as the ratio between the max. soil's shear strength to the minimum value of the shear strength before the failure of the slope. The conventional way to compute the factor of safety with a finite element is to reduce the shear strength until failure occurs. The SRM has two main advantages over the limit equilibrium method. First, it eliminates the assumptions compared to the limit equilibrium method such as the shape and critical slip surface location. Second, numerical methods can simulate the soil/pile interaction. Hence, this is not the case in limit equilibrium methods. Consequently, the SRM usually determines the safety factor to be equal to or slightly less than limit equilibrium methods. In the SRM, simulations are made for several trails of strength reduction factors (Fs) with shear strength parameters c trial and φ trial are modified according to the following equations:

$$c_f = \frac{c}{Fs}$$

$$\varphi_f = \frac{\varphi}{Fs}$$

Where c, φ are the cohesion and the friction angle, c_f & φ_f are cohesion and friction angle after reduction, and Fs is the reduction factor.

2.4- MODEL VERIFICATION

The results from the plaxis model are verified with Bozok's experimental model by comparing the shear force and the bending moment from the experimental model with those from the plaxis model. In Bozok's model, the results from the strain gauges are used to calculate the moment and the shear force depending on three assumptions. First: the steel tube is working alone as the grout is assumed to be cracked; Second: the grout and the steel tube are working together as a composite section; and Third: the "intermediate" and most plausible interpretation was established, assuming that grout under tension will crack meaning that grout in compression mode will contribute to resistance. The experimental results from the three assumptions are shown in Figures 6 and 7, as the horizontal bars expresse the range between values determined using the first and the second assumptions while the dark rhombus shows the results from the third assumption (intermediate). In this study, three models are also implemented using finite element analysis. In the first model, the pile is considered as a steel tube, while in the second model, the pile behaves as a composite section. In the third model, the pile is considered as a concrete pile with its full diameter =0.0387m. The graphs show (Figures 6 and 7) that the results from treating the pile as a concrete pile are close to the experiment results. On the contrary, treating the pile as a steel tube or a composite section gives small reactions compared to the experiment results.

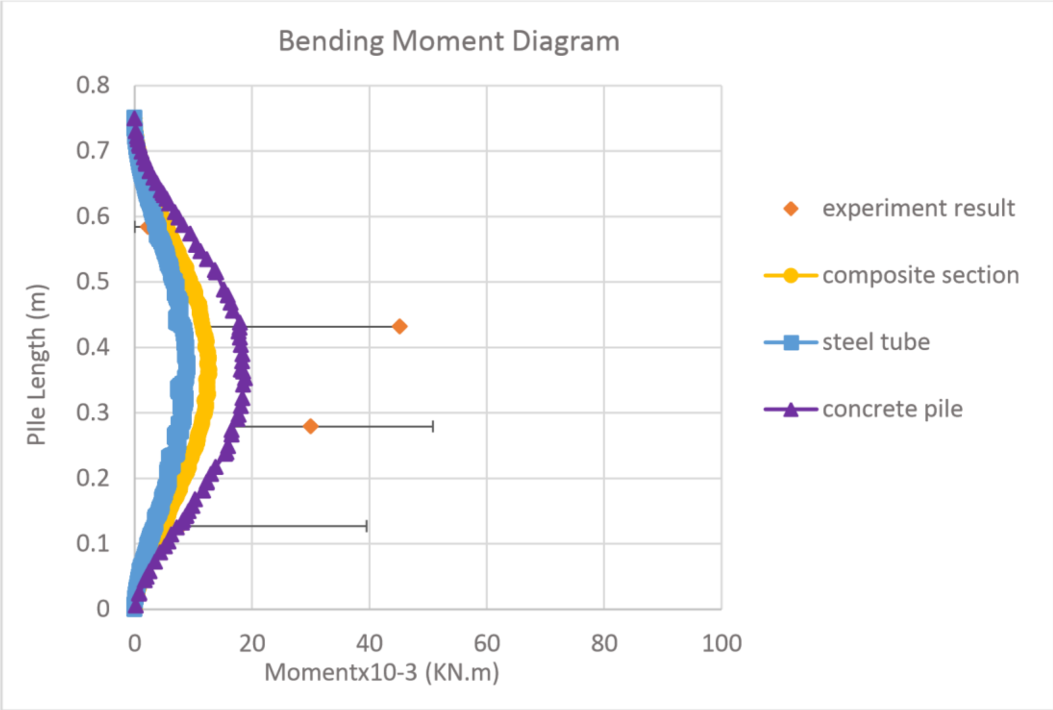


Figure 6 Comparison between bending moment diagrams of FEM with the . Experimental model.

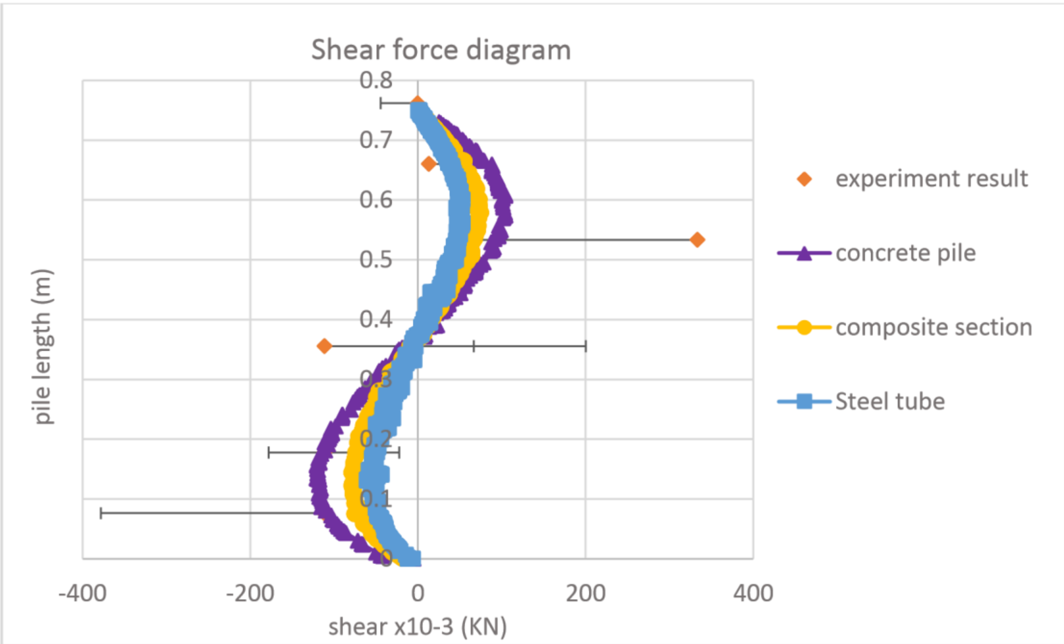


Figure 7 Comparison between shear force diagram of FEM with the Experimental model

3- PARAMETRIC STUDY

The verified finite element model was used to propose the parametric study; however, the model's dimensions were changed to simulate real cases. The slope's size in the Finite element model was 15m long and 12.5m in height with an inclination angle of 40°, the pile diameter equals 0.5m with a starting length of 5m ,and the position of the pile is represented by the ratio h/H as shown in Figure 8.

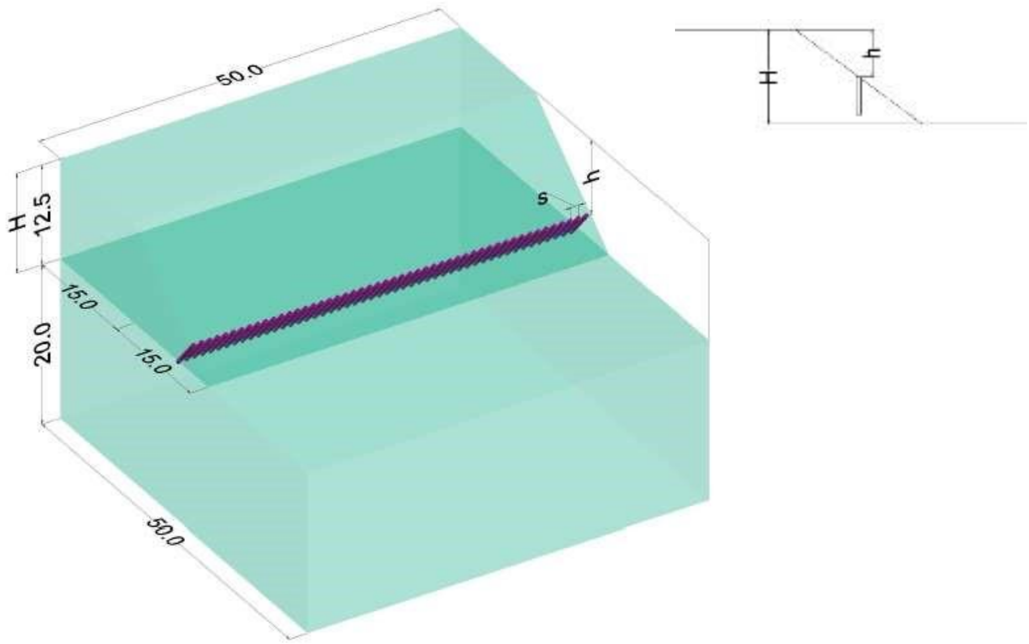


Figure 8 Model geometry.

3.1- EFFECT OF THE PILE POSITION

The pile's position is represented by h/H where h is the distance from the top of the pile to the slope’s crest and H is the height of the slope, which equals 12.5m as this ratio's ranges are 0,0.25,0.50, 0.6,0.75,1. The piles' positions were distributed using different pile spacings 2d,3d,5d,10d with constant pile length = 5m. The study was done on two different angles of installation of the piles, the first one was a vertical pile, and the second one was perpendicular to the surface of the slope. As shown in Figure 9 and Figure 10, the safety factor increases with increasing the ratio h/H until the ratio reaches 0.75. Then the factor of safety decreases with increasing h/H for both vertical and inclined piles. The results show that the best position for the pile is when h/H is between 0.70 to 0.75 and with spacing 3d.

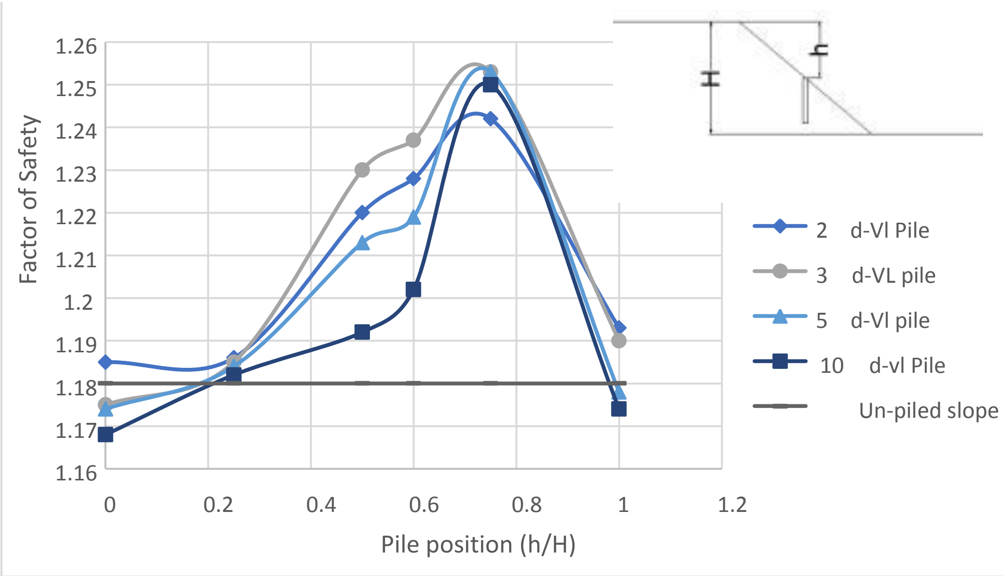


Figure 9 Effect of vertical pile position on factor of safety.

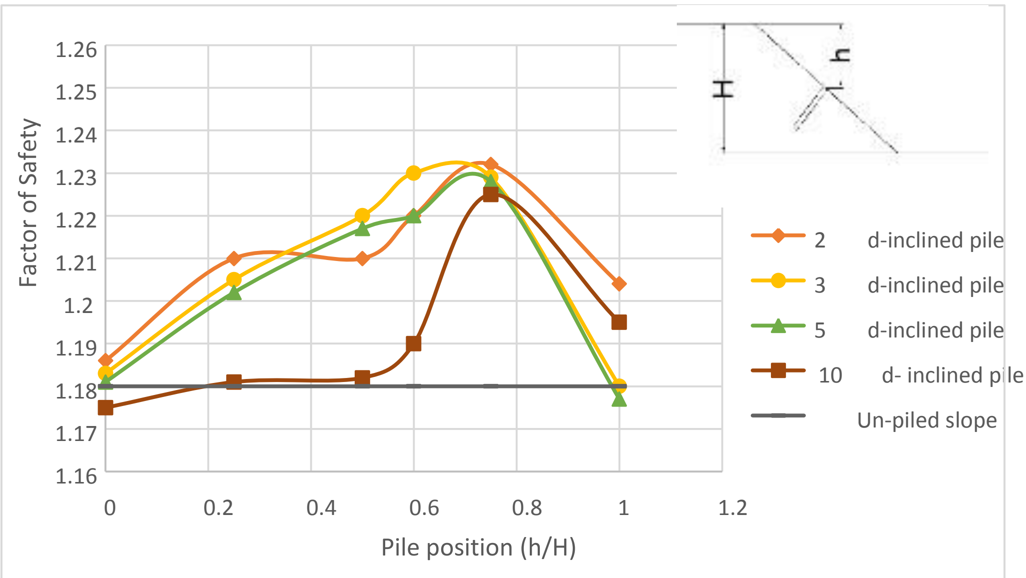
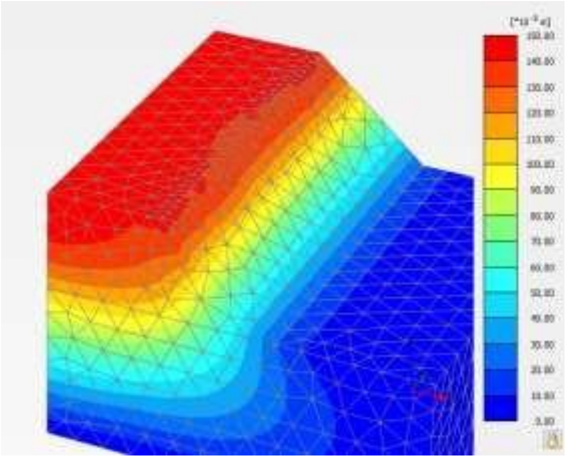
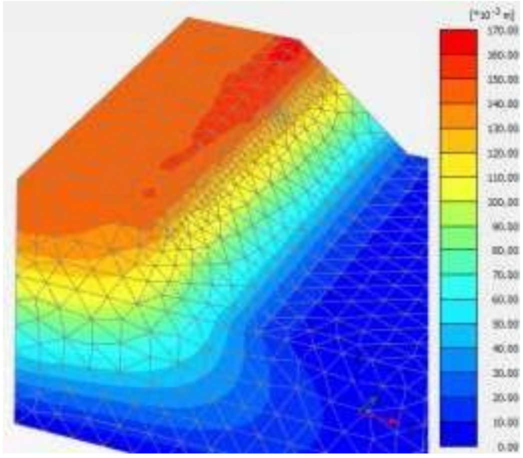


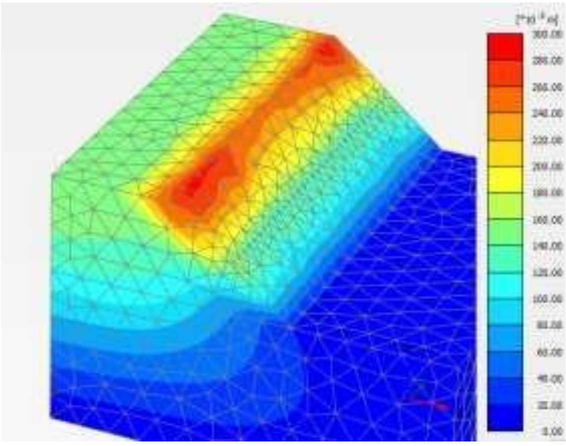
Figure 10 Effect of the position of the inclined pile on factor of safety.



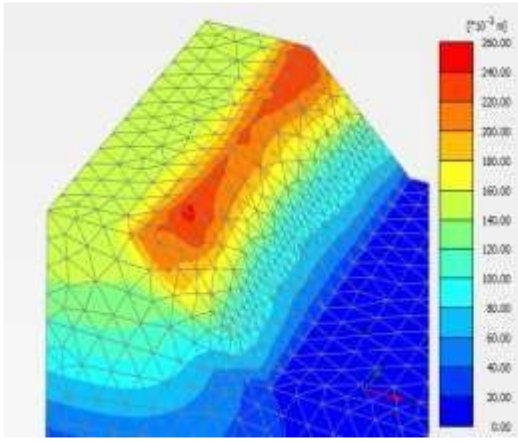
(a) The shape of failure at h/H=0.00



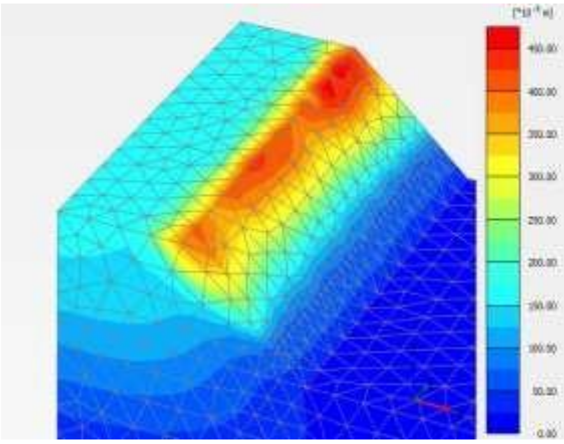
(b) The shape of failure at h/H=0.25



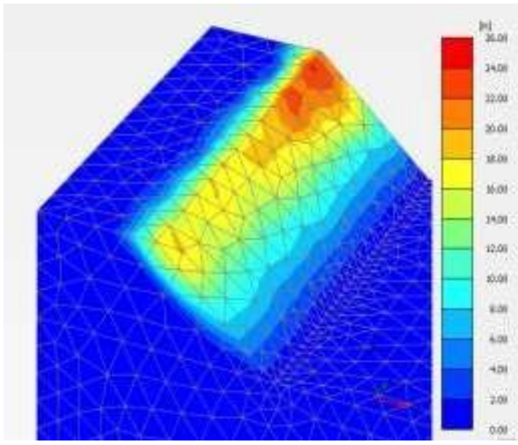
(c) The shape of failure at h/H=0. 50



(d) The shape of failure at h/H=0. 60



(e)The shape of failure at h/H=0.75



(f)The shape of failure at h/H=1.00

Figure 11 The shape of failure at different piles' positions with spacing between the piles=3d& the pile is vertical.

The pile position also affects the shape of the slope's failure so different piles position with spacing between the piles equals 3d as it gives the max. safety factor will be invistigated, as shown in Figure 11. As shown in Figures 11a &11b, the failure occurs all over the slope When the pile is near the top of the slope (h/H=0 or 0.25). The factor of safety doesn't change compared to the un-piled slope model. By increasing the value of h/H from 0.5 to 0.75, the slope's stability increases, and the shape of failure improves, as shown in Figures 11-c,11-e & 11-d. The piles have a nil effect when located at the slope's toe, as shown in Figure 11-f.

3.2- EFFECT OF THE SPACING BETWEEN THE PILES

The effect of pile spacing (s) on the factor of safety is investigated on various spacings such as 2d, 3d, 5d, and 10d, where d is the diameter of the pile, as shown in Figure 12. This effect is also studied on many piles' positions for both vertical and inclined piles.
The pile length =5m and the diameter of the pile =0.50m, as shown in Figures 13,14&15

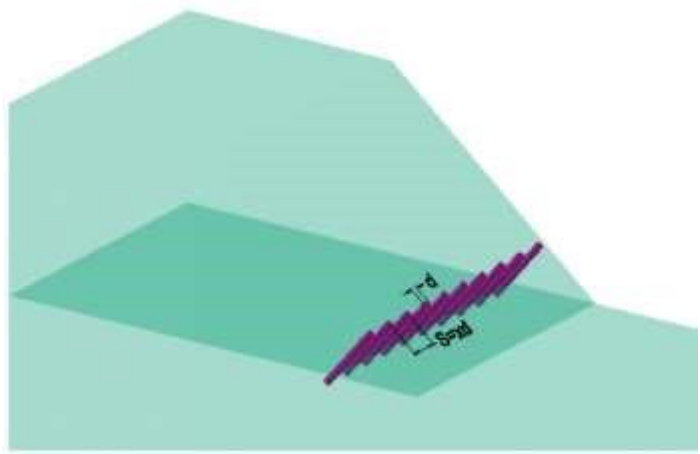


Figure 12 Model configuration

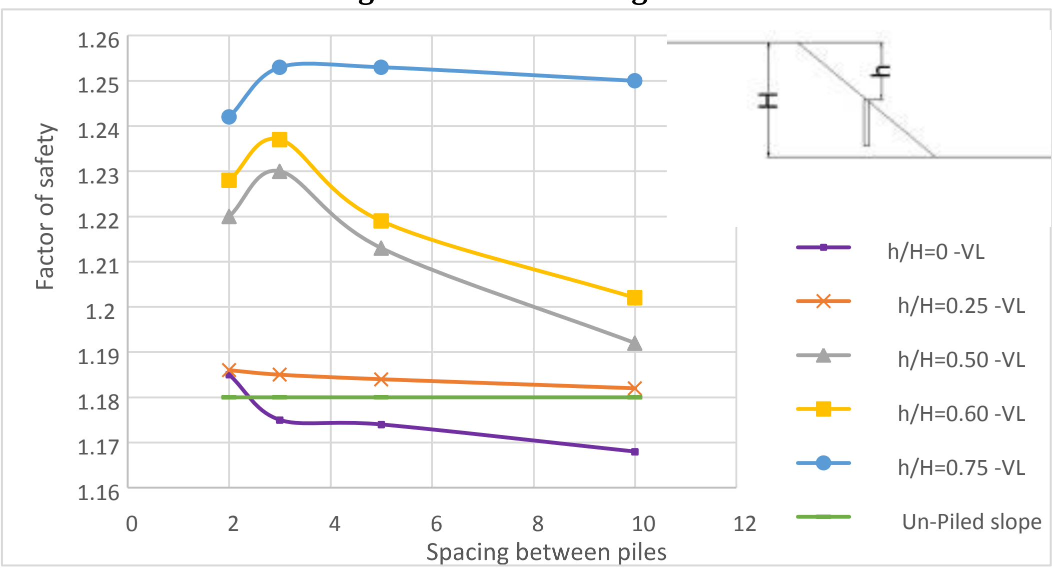


Figure 13 Effect of pile spacing when the piles are vertical to the slope.

As shown in Figure 13, when the piles are at h/H=0.00 and 1.00, the safety factor's changes are barely noticeable, but when h/H=0.25, 0.50, and0.60, the safety factor decreases by 3% with increasing the spacing between the piles. After spacing 3d the decrease or increase for various h/H is nearly negligible.

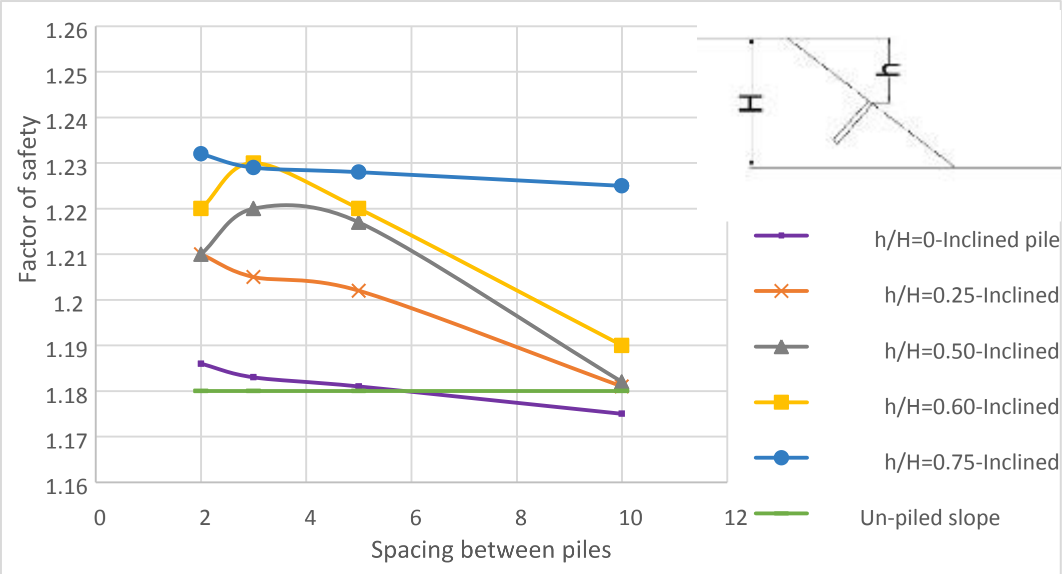


Figure 14 Effect of pile spacing on factor of safety when the piles are normal to the slope.

When the piles are normal to the slope (inclined piles), as shown in Figure 14, the safety factor changes when the piles are near the toe or the crest (h/H=0.00&0.75) is too small. When the piles are in the middle of the slope, the rate of change in the safety factor is noticeable, while the increasing of the spacing between the piles results the decrease of the factor of safety.

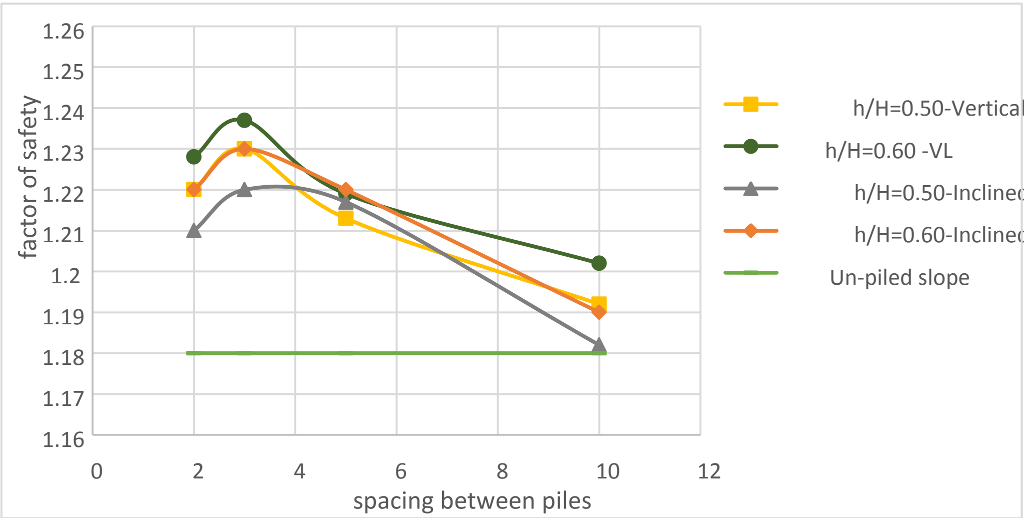


Figure 15 Comparison between the vertical and the inclined piles' responses in terms of the factor of safety when changing the piles' spacings.

Figure 15 shows that changing of the piles' inclination results in changing in the factor of safety higher values for vertical pile.

3.3- EFFECT OF THE PILE LENGTH

Four pile lengths 5,7,10& 12 m were investigated to study the effect of the pile length(L) on the factor of safety when the pile position is at 0.75 h/H, the spacing between piles is =2d, and the diameter of the pile (d)=0.5m. As shown in Figure 16, the safety factor increases by increasing the pile length until the length reaches 10 m. After that, the changes are too small. The figure shows that the best pile's length under the slope compared to the slope length =0.67H where H is the height of the slope. To further investigate the best length of the pile under the slope, the following study is conducted.

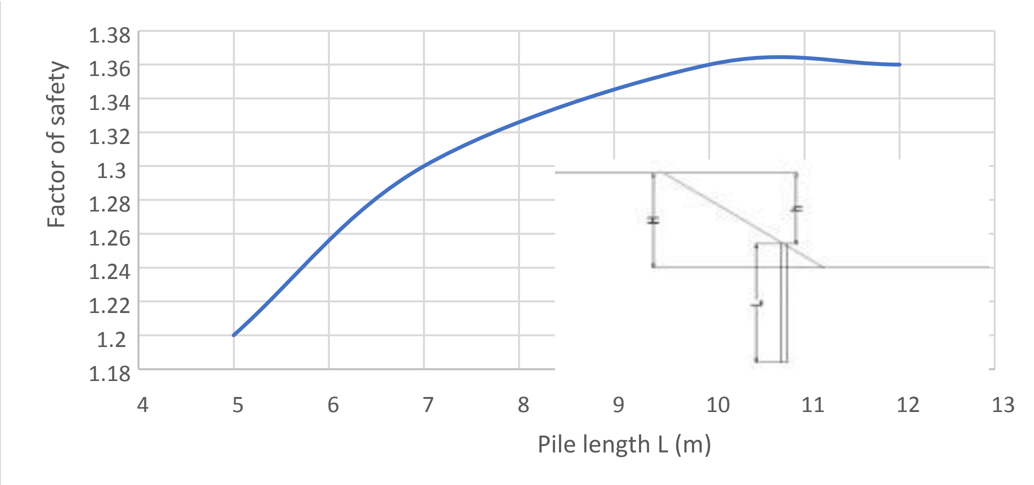


Figure 16 Effect of the pile length on factor of safety

The length of the pile under the slope is studied in various positions where h/H=0.00,0.25,0.50,0.60, 0.75, and 1.00 to study its effect on the factor of safety. The length of the pile under the slope is represented by Z/H, where Z is the length of the pile under the slope toe, and H is the height of the slope, as shown in Figure 17. Spacing between the piles equals 2d, where d=0.5m.

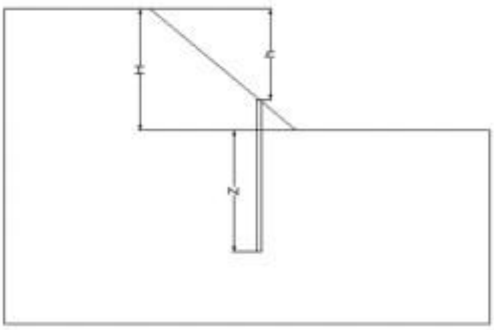


Figure 17 Schematic view

Figure 18 shows that when the piles are at position h/H=0.60 and 0.75, the safety factor increases by 10% with increasing Z/H until the ratio becomes 0.60, then the changes in the factor of safety is nearly negligible, which is the same result mentioned above Figure16. In the case of the piles' position is at h/H=0.50, the factor of safety keeps increasing up to

16% by increasing Z/H until the ratio becomes 0.9. On the other hand, when h/H=1.00 or 0.25, the changes in the factor of safety are too small with increasing Z/H. When the pile is at h/H=0.00, the factor of safety is close to the factor of safety of the un-piled slope.

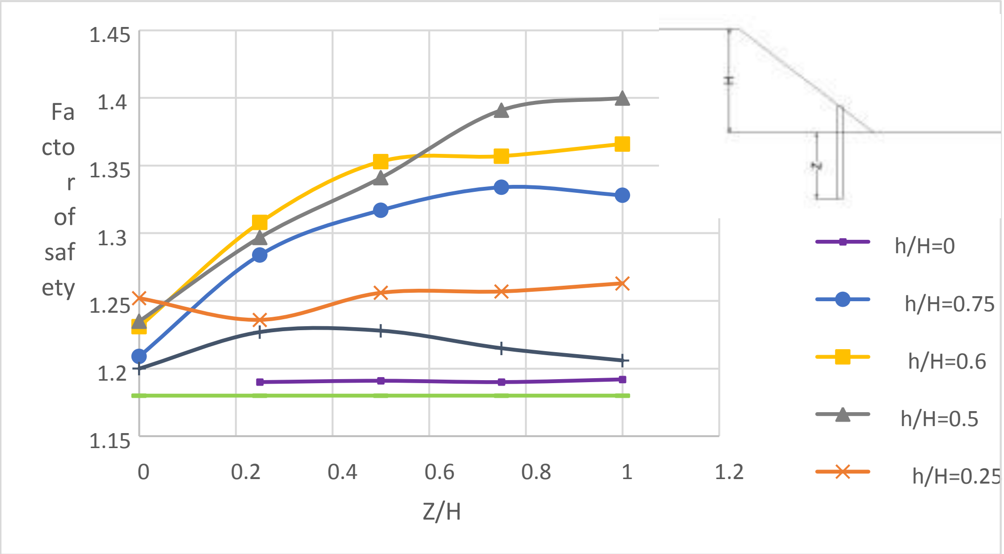


Figure 18 Effect of the length of the pile under the slope on factor of safety.

3.4- EFFECT OF THE PILE DIAMETER

The vertical piles with pile length =10 m located at h/H=0.75m and spacing between piles is 1.0 m is considered for the study of the effect of the pile diameter on the factor of safety where the pile diameter varies from 0.50 to 1.00 m. As shown in Figure 19, the factor of safety of the slope barely increases (i.e.0.7%)with increasing the pile diameter.

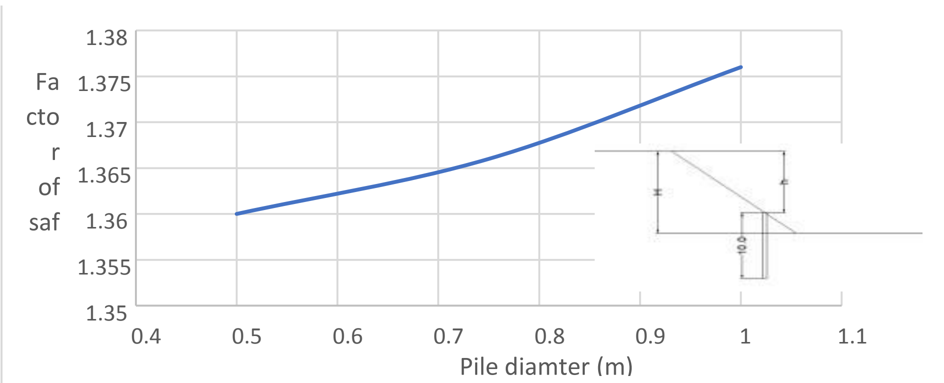


Figure 19 Effect of the pile diameter on factor of safety.

3.5- EFFECT OF PILE CONFIGURATIONS

Vertical and inclined piles with length (L) = 10 m, the diameter(d) =0.50 m, and spacing between piles (s) =1.5 (3d)m are used in four configurations to study their effect on the factor of safety as shown in Figures 20.

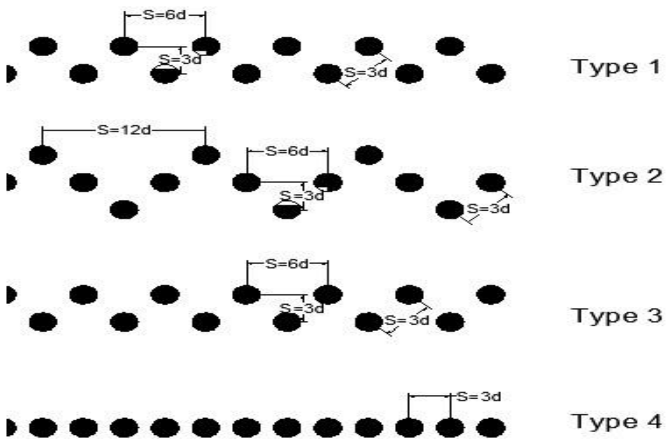


Figure 20 Plan for different configurations types

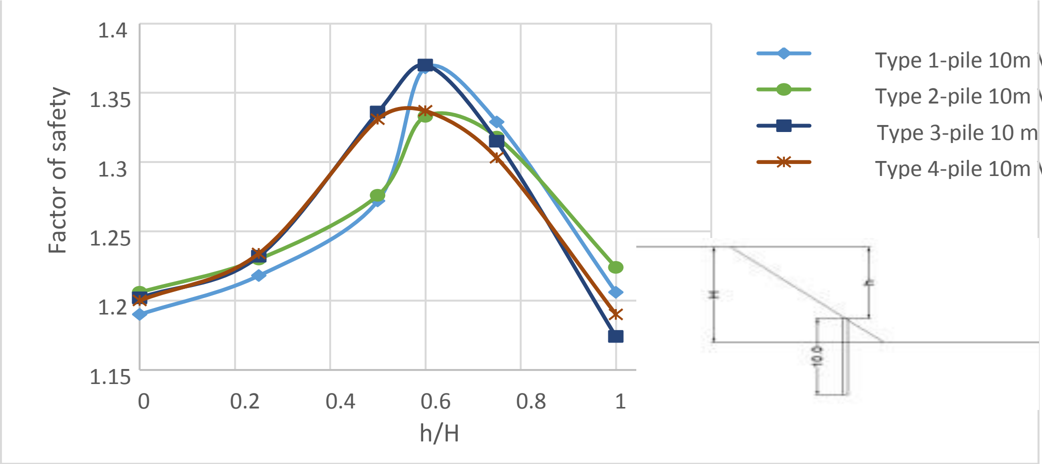


Figure 21 Effect of pile configuration on the factor of safety for vertical pile with length= 10m

Figure 21 shows that when the pile near the top of the slope (h/H=0 to 0.3),the effect of changing the configuration of the pile on factor of safety is nearly negligible but when the piles are in the middle or near the slope's toe the factor of safety is increasing by changing the configuration of the piles especially when using type one or three. On the other hand, using type two doesn't affect the factor of safety so it is not recommended to use it.

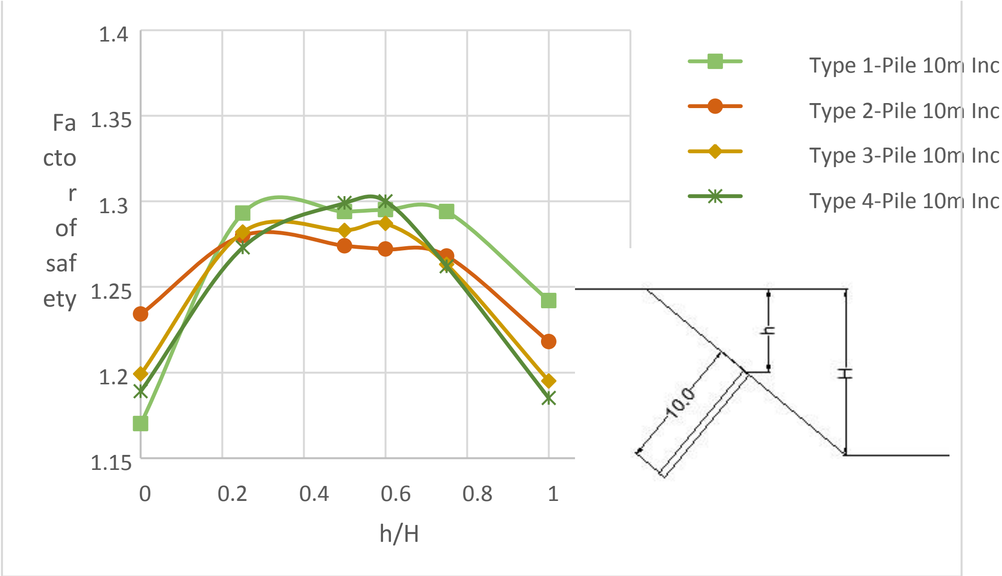


Figure 22 Effect of pile configuration on the factor of safety for the inclined pile with length =10m.

Figure 22 shows that, when the piles near the top of the slope (h/H=0 to 0.2), the factor of safety increases with arranging the piles as type 2 but when the piles in the middle of the slopes(h/H=0.4 to 0.6), the factor of safety decreased with changing the configuration so it is recommended to arrange the pile as type 4. When the piles near the toe of the slope (h/H=0.75 to 1) it is recommended to use type 1or 2 as it gives the maximum factor of safety.

4- SUMMARY AND CONCLUSION

A 3D model was developed by using Plaxis 3D implementing the shear strength reduction method to simulate the coupled pile-slope interaction and conveniently calculate the global factor of safety. This model was verified with a large-scale experimental model. The 3D model was used in a parametric study varying the piles' parameters such as the pile's position, inclination, length, diameter, and configurations. The following conclusions are found out:

1. The optimum pile position is in the slope area where h/H=0.5 to 0.75 as it gives the maximum factor of safety, especially when the length of the piles under the slope toe (Z/H) = 0.6 of the height of the slope.
2. The safety factor decreases by increasing the piles' spacing, especially in the middle area of the slope. When the piles are near the slope's crest, the change in the safety factor is nil.
3. In case of increasing the pile diameter, the improvement of the factor of safety is insignificant, so it is not recommended to increase the pile diameter more than 0.5m.

4. When the pile length increases, the safety factor increases until the pile's length under the slope (Z/H) =0.6H, where H is the height of the slope. After that, the change is too small.

5. It is recommended to adjust the vertical piles configuration as type one or type two, especially when piles are in the middle of the slope as slope's stability increases.

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