

Simplified Analysis of Slope Stabilizing Piles

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Abstract: Slope stabilizing pile is one of the most effective ways to reinforce a slope with soil arching effect, in which the interslice forces transmitted to the soil slice behind the piles is reduced. Limit equilibrium based slope stability analysis technique is used in this paper to ascertain factor of safety of slope as well as to quantify forces within the piles. Load transfer factor has been used to estimate net force imparted on the piles with respect to influencing factors such as spacing and pile properties, slope geometry, soil-strength parameters and pile location on the slope. The present study includes analysis of slope with and without piles to verify the results based on this approach to those proposed by other researchers.

Keywords: Slope stability, piles, load transfer factor, parametric study.

I. INTRODUCTION

There are numerous methods in slope stabilization including geotextiles, nails, piles, and pitching (Abramson, 1996; Ahmed, 2015). Soil nailing and micropiles are among the most efficient ways to internally stabilize a slope. (Joorabchi, 2011). Common design methods for slope stabilizing piles may be categorized into pressure or displacement based method (De Beer and Wallays, 1972; Ito and Matsui, 1975; Poulos, 1995) and numerical methods (Cai et al. 2002; Liang and Zeng, 2002; Kourkolis et al. 2011). For the former case, the pile is subjected to presumed slope displacement, distribution of soil modulus and limiting values of pile-soil contact pressure. For the latter case, numerical method such as finite elements is used to analyze the slope stabilizing pile system. It is complicated and time consuming as it involves 3D problem in terms of soil geometry, soil structure interaction and pile group effects (Kourkolis et al. 2011). Most of the common analysis and design methods are based on limit-equilibrium approach, which means the presence of piles is to increase its resistance towards the soil. Alternative approach of the same concept of limit equilibrium method of slices has been proposed by Liang et al. (2014) in which the effect of piles is considered to reduce the driving forces due to soil arching between the adjacent piles. A load transfer factor, η , has been developed by Zeng and Liang (2002) and Liang and Zeng (2002) using 2D finite element parametric analysis and later in extensive 3D finite-element simulation to better represent the soil-structure interaction phenomenon. The advantage of the proposed method is to estimate the behavior of piles subjected to lateral soil movements due to slope instability which is established through a number of full scale load tests (Mujah et al. 2013).

The objective of this paper is to present a simplified approach to analyze the pile stabilized slopes based on the load transfer factor to determine the driving force of the sliding soil mass that acts along the pile segment above the slip surface and the overall slope stability is then analyzed using limit equilibrium approach. The effects of pile location in slope, pile spacing, and slope geometry, and water table is presented and discussed.

II. METHOD OF ANALYSIS

Limit equilibrium based method of slices is used in the proposed method to calculate global factor of safety of one or more rows of piles in pile-slope system. The arching force acting on a row of piles due to soil movement is evaluated using the load transfer factor proposed by Liang et al. (2014).

Load transfer factor, η , is defined by Liang et al. (2014) as the ratio between the horizontal force on the downslope side of the vertical plane at the interface between the pile and soil to the horizontal force on the upslope side of the vertical plane at the interface between pile and soil. General characteristics of load transfer factor are affected mainly by soil strength parameters (c , ϕ), pile diameter (d) and slope geometry (s/d , ξ_x , β). The load transfer factor can be expressed as (Liang et al. 2014):

$$\eta = -0.272c^{0.153}(\tan\beta)^{-0.429} (-1.17 + 1.114\frac{s}{d}) \times [e^{(-0.578\tan\phi)}] (0.065+0.876d) \times [-0.252 + 0.61\xi_x - 0.57(\xi_x^2)] \quad (1)$$

$$0 < \eta < 1.0 ; L_R > 0.15L_P$$

where c = soil cohesion, β = slope angle, s = pile spacing, d = pile diameter, ϕ = soil friction angle, ξ_x = pile location (x_i/x), L_R = length of pile embedded in rock, L_P = total pile length.

The limit-equilibrium approach such as the modified Bishop method of slices is used to analyze the overall slope stability. The safety factor of the pile-stabilized slope is determined by including the total resistance provided by piles in one unit length of the slope is given as:

$$FS = \frac{F_{RS} + F_{RP}}{F_{DS}} \quad (2)$$

where F_{RS} = resisting force of soil mass, F_{RP} = resisting force produced by piles, F_{DS} = driving force of sliding soil mass. The resisting force produced by the piles is determined using the load transfer factor approach (Eqn. 1) as suggested by Liang et al. (2014):

$$F_{RP} = (1 - \eta) P_L \quad (3)$$

where P_L = interslice force acting on the left side of the slice and s = center to center spacing of piles. Fig. 1 shows the slope geometry for an illustrative design example used by Liang et al. (2014). It is employed here to verify the proposed method for analyzing the pile-stabilized slopes. Fig. 2 demonstrates that the results computed by the rigorous finite-element method (Liang et al. 2014) and the proposed simplified method are in good agreement. The computed normalized factor of safety ($= \frac{FS_{(piles)}}{FS_{(no\ piles)}}$) computed by both methods indicates that the factor of safety tends to increase with pile location (measured by the distance from the crest of slope) but it decreases with increasing pile spacing.

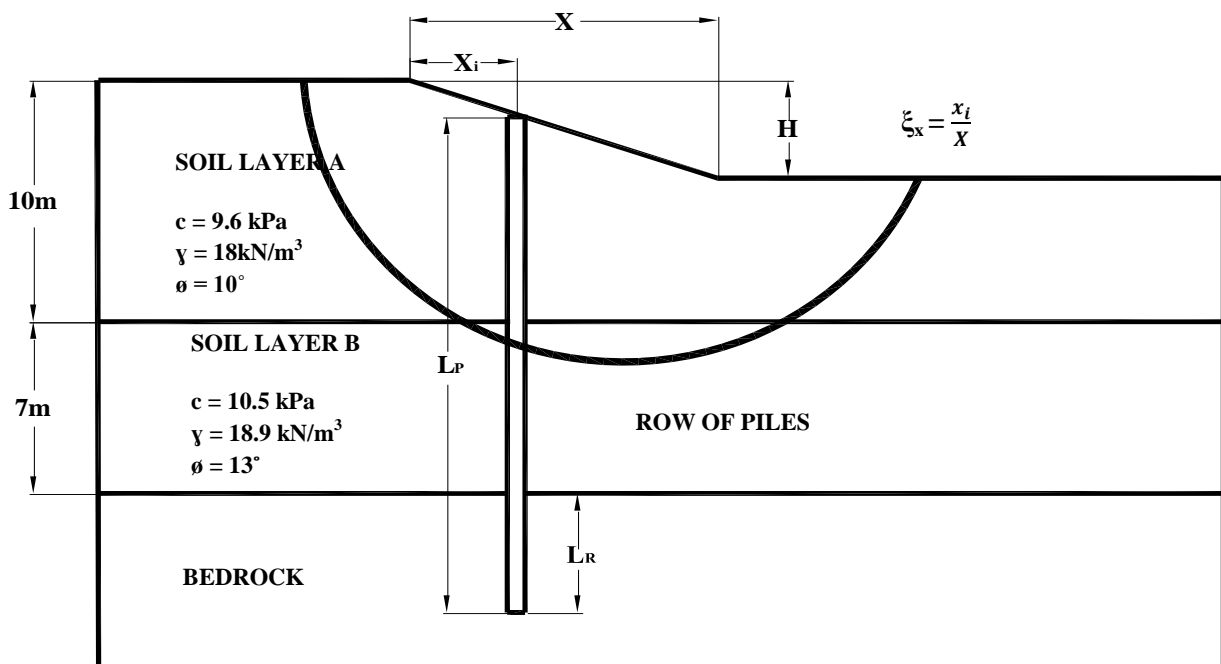


Fig. 1: TYPICAL EXAMPLE OF PILE STABILIZED SLOPE

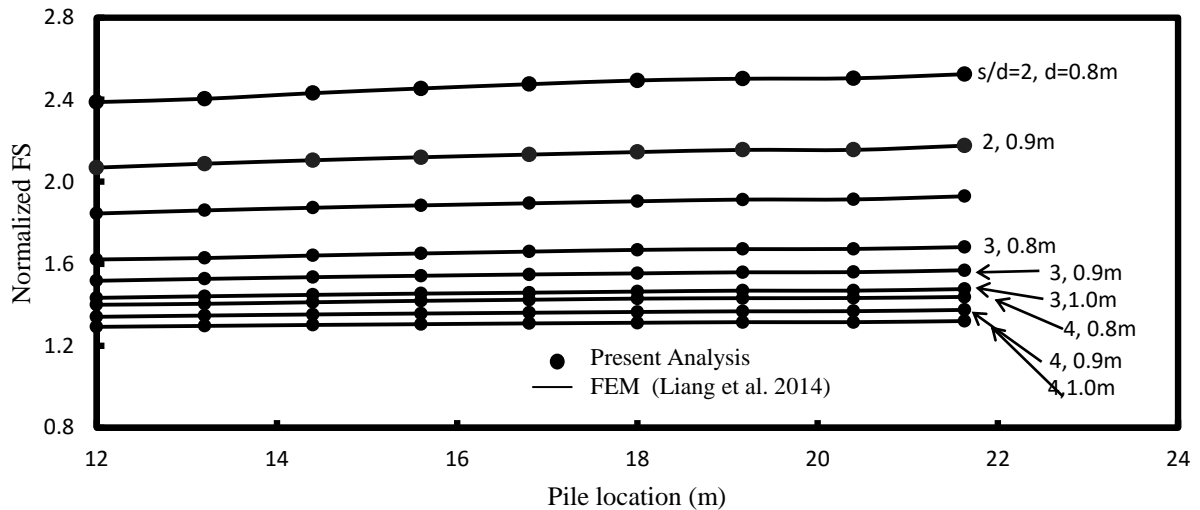


Fig. 2: EFFECT OF PILE LOCATION AND SPACING ON NORMALIZED FACTOR OF SAFETY

III. PARAMETERS AFFECTING THE PILE-STABILIZED-SLOPE

There are several parameters which may affect the pile-stabilized slopes and some of them can be outlined as the soil properties, pile properties, pile location in the slope, pile spacing and load transfer factor. Fig. 3 exhibits the comparison of the results computed by the present analysis to those of Liang et al. (2014) on the effect of pile location (ξ_x) and pile spacing on the load transfer factor, η . Both results show good agreement. The load transfer factor, η , increases with increasing pile spacing because the row of piles tends to behave as a single pile and the soil loses its arching effect as the spacing between adjacent pile increases. However, the magnitude of η decreases with increasing pile location, ξ_x , until the location of a pile reaches about the middle of slope and then it starts to increase (Liang et al. 2014).

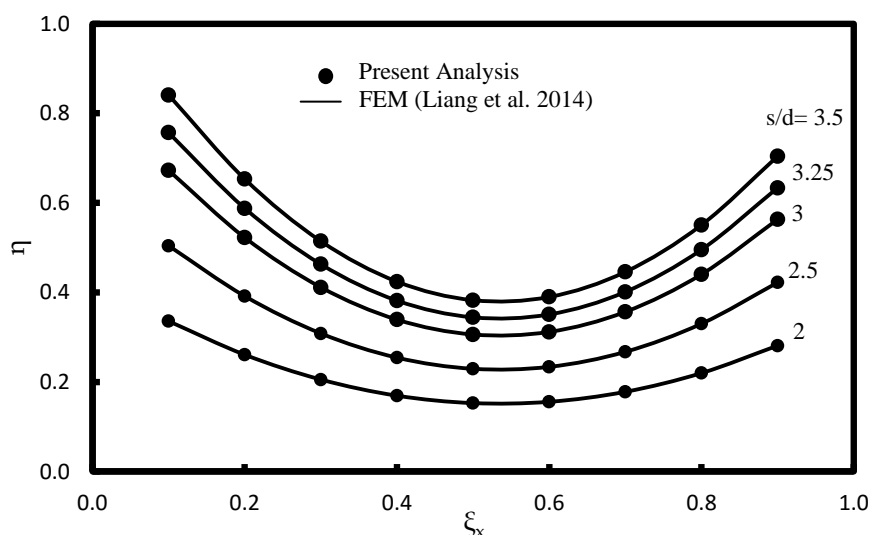


Fig. 3: EFFECT OF ξ_x AND s/d ON η , ($d=1.0m$, $\phi=10^\circ$, $c=24kPa$, $\beta=40^\circ$)

It is found that load transfer factor, η , decreases with increasing slope angle, β , as shown in Fig. 4(a). As the inclination of slope increases, gravity-induced driving force, F_{DS} , also increases implying a smaller load transfer factor, η , inducing a higher pile resisting load, F_{RP} , as illustrated in Eqn. (3). However, the load transfer factor, η , decreases with increasing pile diameter until a certain limit (Liang et al. 2014). Fig. 4(b) shows that the load transfer factor, η , decreases as the soil friction angle and cohesion increases, inducing a higher pile resisting load.

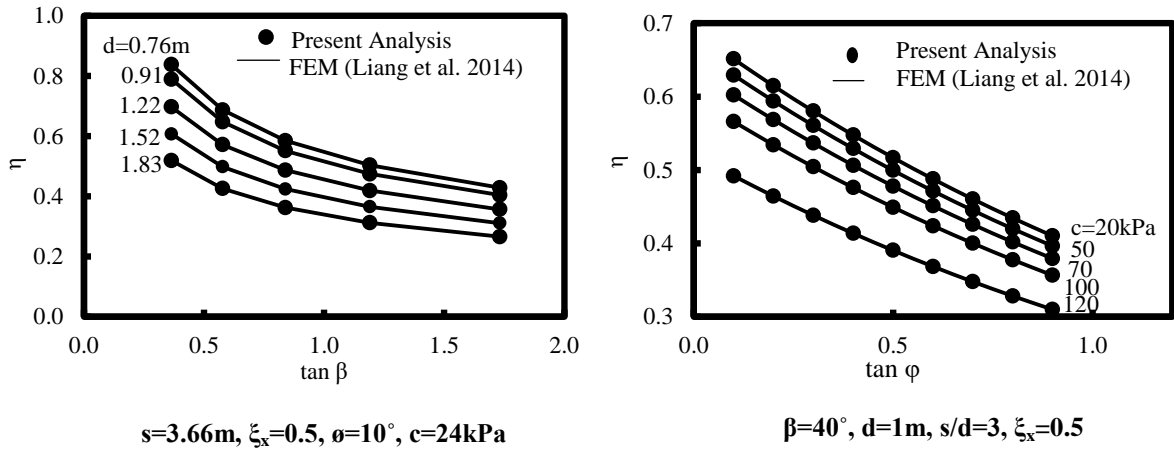


Fig. 4: EFFECT OF c , ϕ , β AND d ON η

As can be seen in Fig. 5, the normalized F_{RP}/F_{RS} tends to increase with pile location (measured by distance from the crest of slope) and then decreases when the location of piles is beyond the center of slope. The location of piles in the center of slope provides the largest normalized pile load and it decreases when the piles are moved further downslope.

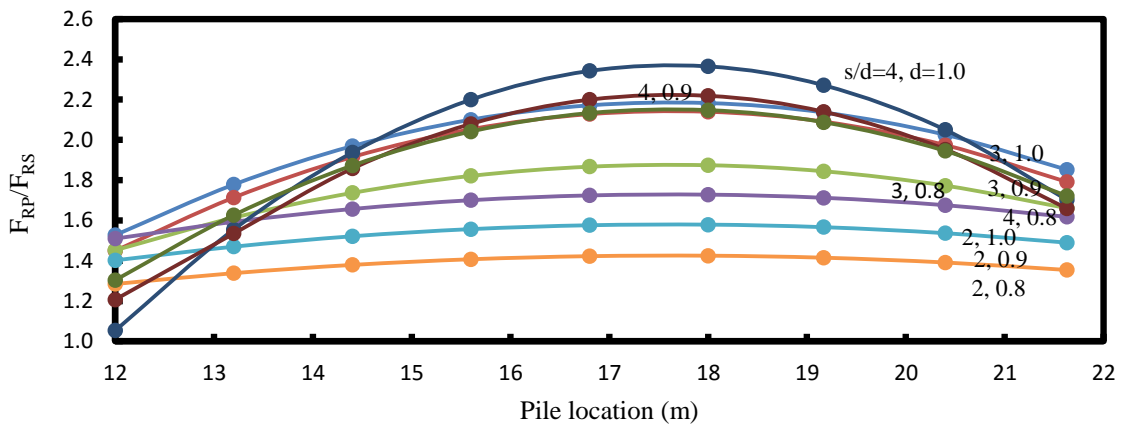


Fig. 5: NORMALIZED F_{RP}/F_{RS} VS PILE LOCATION

Fig. 6 shows the effect of stabilizing pile diameter, d , on the resisting pile force, F_{RP} , with respect to their locations in the slope for three different pile spacing ($s/d = 2, 3, 4$). It was found that the resisting pile force, F_{RP} , increases with pile location and it decreases when the location of pile is beyond the centre of the slope. However, the pile diameter and spacing appear to have little effect on the resisting pile force, F_{RP} .

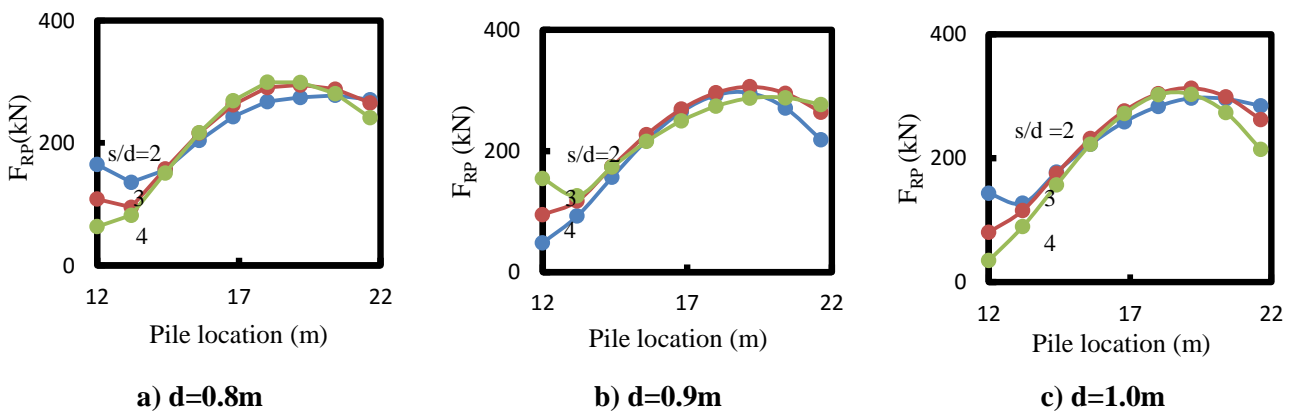


Fig. 6: EFFECT OF PILE LOCATION AND DIAMETER ON F_{RP}

IV. CONCLUSIONS

This paper has presented a simplified method for the analysis of slope stabilizing piles. The simplified method employs the limiting equilibrium based slope stability procedure that incorporates stabilizing piles which induced arching effects using load transfer factor as suggested by Liang et al. (2014). The proposed simplified method accounts for the effects of slope geometry, soil properties, pile spacing, pile diameter and pile location in the slope. The computed results based on the proposed simplified method agreed well with some rigorous finite-element results. However, it should be emphasized that the accuracy of the proposed simplified method is validated only for limited range of slope geometry, soil and pile properties. Hence, the capabilities of the proposed simplified method require further detailed investigation.

ACKNOWLEDGEMENT

The assistance and support from Ministry of Education (MOE) and ERGS grant are gratefully acknowledged.

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