Investigation of load transfer factor of slope with drilled shaft

Wei-Chien Wang[1], H.-D. Lin[1], and A.-J. Li[1]

[1] Dept. of Civil and Construction Engineering, National Taiwan University of Science and Technology, No.43, Keelung Rd., Sec.4, Taipei 10607, Taiwan (R.O.C.)

ABSTRACT

Slope stability is an important issue in Taiwan because of the limited spaces of urban lands. Using drilled shafts to stabilize the slope becomes more popular due to its reliability, suitability, and eco-friendliness. The contribution of the drilled shaft to slope stability can be explained by the soil arching effect. This effect can be quantified by the load transfer factor (η) that is the ratio of the horizontal forces acting on the down-slope and the up-slope of shaft piles. Since the calculation of η relies on the depth of failure surface, a reasonable approach to determine the depth of the failure surface is definitely required. Three ways are studied to investigate the effects of potential failure criteria (displacement, plastic zone or shear strain increment) on the load transfer factor. Additionally, the relationship between the depth of sliding surface and η value is studied considering various soil strength parameters (c and ϕ).

Keywords: drilled pile; load transfer factor, slope stability, soil arching

1 INTRODUCTION

Placement of drill shafts in a slope is one of the feasible remediation measures that can be done to increase the factor of safety in order to meet the safety requirement.

Liang (2010), Liang and Yamin (2010), Liang and Zeng (2002) provided a series of studies on the behavior of the drilled-shaft slopes by using ABAQUS program. In their studies, the concept of soil arching was adopted to account for the stabilization effects of the drilled shaft installed in the slope. In particular, the effectiveness of the drilled shaft is quantified by a load transfer factor (η). The definition of the η will be explained in Section 2.2.

Because the calculation of η relies on the depth of failure surface, a reasonable approach to determine the depth of the failure surface is necessary. Thus, this research adopts the 3D model from Liang and Yamin (2010) to study the effects of potential failure criteria (displacement, plastic zone or shear strain increment) on the load transfer factor.

2 PREVIOUS STUDIES

2.1 Soil Arching

In 2002, Liang and Zeng proposed a new method to address the effect of drilled shafts on the factor of safety of a slope considering the soil arching effect. Factor of safety was calculated by reducing the driving force for the portion of soil on the down-slope side of the drilled shafts due to soil arching. Equation (1) describes the analytical method for calculating the factor of safety:

$$FS = \frac{F_R}{F_D - (\Delta F_D)_{arching}} \qquad (1)$$

Where FS is global factor of safety of a slope/shaft system, F_R = resistance force, $(\Delta F_D)_{arching}$ is drilled shaft induced arching effect on driving force.

2.2 Load Transfer Factor (η)

The load transfer factor (η) is defined by Liang (2010) to quantify the effectiveness of the drilled shaft. The definition of η is the ratio between the lateral force of the down-slope and that of the up-slope as shown in Figure 1. It can be expressed mathematically as:

$$\eta = \frac{P_{down}}{P_{up}} \qquad (2)$$

Where P_{up} is the horizontal force on the vertical plane at the interface between drilled shaft and soil on the up-slope side, P_{down} is the resultant horizontal force on the down-lope side.

$$P_{up} = \int_0^{L_f}\int_0^{n} \sigma_x d_y d_z \qquad P_{down} = \int_0^{L_f}\int_0^{n} \sigma'_x d_y d_z \qquad (3)$$

Where S is the distance between center to center of two adjacent shafts, L_f is the distance from top of the shaft down to the failure surface, σ_x is the horizontal soil stresses on the up-slope side of the shaft, σ'_x is the horizontal soil stresses on the down-slope side of the shaft.

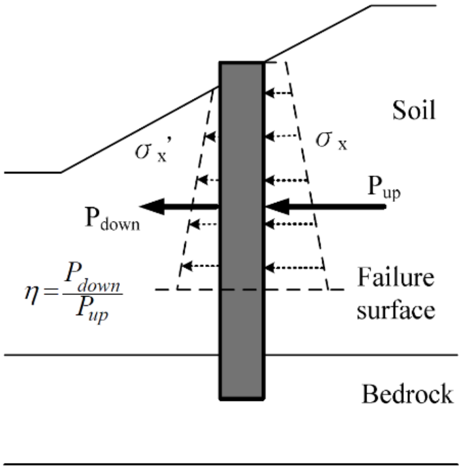

Fig. 1. Definition of the load transfer factor (Lin et al., 2011)

In theory, η must be less than one and greater than zero. “Zero” indicates the drilled shafts act like a wall to block the entire earth pressure, while “One” represents the slope without any soil arching effect, which means drilled shafts provide no contribution.

Liang and Zeng (2002) used numerical analysis method to discuss the effect factor of soil arching, including pile diameter, soil strength parameters, the ratio of pile spacing and diameter, and the position of the drilled pile. Thereafter, Liang and Yamin (2010) conducted a series of parametric studies using ABAQUS program with shear strength reduction method (SRM). Their study indicated that the influence factors are sequentially pile diameter (D), friction angle (ϕ), position of drilled pile (ξ), the pile spacing/diameter ratio (S/D), and cohesion (c). Following the work of Liang (2010), Lin et al. (2011) adopted PLAXIS 3D Foundation, a finite element package, to examine the feasibility of using the drilled shaft as a way to stabilize the slope in Taiwan. The following suggestions can be drawn from Lin et al. (2011, 2013): (1) Pile diameter and pile spacing should be carefully evaluated to assure that soil arching can develop to reduce the driving force; (2) important design parameters are the pile spacing, diameter ratio (S/D), and the location of the pile; (3) the most effective zone to install the drilled shaft is in the middle portion of the slope.

2.3 Potential Failure Mechanism

How to estimate the failure surface of a slope is an important issue. There are three common ways to decide the position of the failure surface: displacement, plastic zone or shear strain increment.

Three failure mechanisms above have been adopted in relevant papers. Matsui (1992) examined failure surface using shear strain method. The plastic zone is used as the basis for judging failure surface, including Li et al. (2009, 2010), Qian et al. (2014), and Lim et al. (2015). They used the limit analysis methods to discuss slope stability factors of 2D or 3D slopes on different material conditions. Finally, Wei et al. (2009, 2010), Liu et al. (2016) and Kelesoglu (2016) used FLAC^{3D} to determine failure surface based on shear strain mechanism. According to displacement mechanism, Cai and Ugai (2000), Lin et al. (2013) used FLAC^{3D} to observe the position of failure surface.

3 METHODOLOGY AND NUMERICAL MODEL

The baseline model is similar to the model conducted by Liang (2010). To begin with, the baseline model without the drilled shafts was analyzed by PLAXIS 3D using SRM. The results, including FS and the position of sliding surface, were compared to Liang’s results to ensure the baseline model was correct and reasonable. The next step is to insert the drilled shafts into the baseline model. Then the SRM was performed to obtain the FS and to observe the stress distribution in the form of arching. Based on three different failure mechanism (as mentioned previously), the depth of sliding surface was determined. Then, the results were compared and discussed, including the depth of sliding surface and the load transfer factor. Finally, the influence of soil strength parameters (i.e. ϕ=10°, 20°, 30°; c= 19, 48, 72 kN/m^2) on the depth of sliding surface and the η are discussed.

Figure 2 shows a sketch of the slope geometry with the drilled shafts that is used as the numerical model in this study. In this study, soil is modeled as a linearly elastic-perfectly plastic material that follows the failure criterion of Mohr-Coulomb. The summary of parameters used in the study is shown in Table 1.

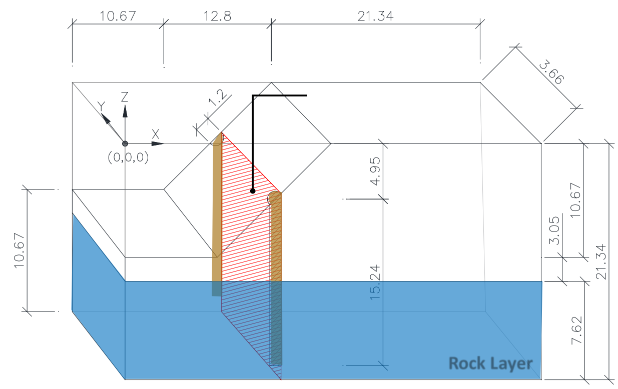

Fig. 2. Baseline model with the drilled shafts (Redraw from Liang, 2010)

According to the verification of baseline model, the factor of safety (FS=1) is the same as Liang (2010), and the position of sliding surface is consistent with Liang (as shown in Figure 3).

Table 1 Parameters for materials in numerical model

Type	Parameter	Value

		PLAXIS 3D (This study)	ABAQUS (Liang, 2010)
Soil	ϕ	10°、20°、30°	10°
	c	19、48、72 kN/m^2	400 psf
	E_s	9576 kN/m^2	2×10^5 psf
	γ_d	18 kN/m^3	115 pcf
	ν	0.3	-
	Material model	Mohr-Coulomb	Mohr-Coulomb
	Material property	Drain	-
Rock	E_r	2.4×10^7kN/m^2	5×10^8 psf
	γ_d	26 kN/m^3	-
	ν_r	0.2	0.2
	Material model	Linear elastic	Linear elastic
	Material property	Non-Porous	-
Pile	E_p	2×10^7 kN/m^2	4.2×10^8 psf
	γ_d	23.5 kN/m^3	-
	ν_p	0.2	0.2
	Material model	Linear elastic	Linear elastic
	Material property	Non-Porous	-
Slope geometry	Slope angle	40°	40°
	Location of pile	Middle of slope	Middle of slope
Interface	Soil-Pile	R_{inter}=0.5	tanδ=0.3

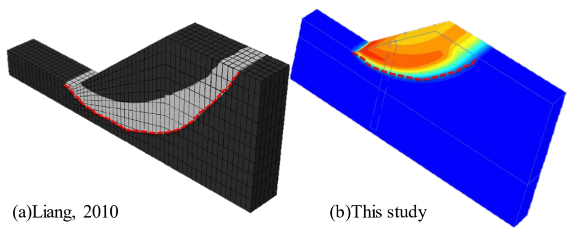

Fig. 3. Comparison with Liang(2010) on potential failure surface

4 RESULTS AND DISCUSSIONS

In this paper, the depth of potential failure surface under three different mechanisms are compared and discussed. Figure 4 shows that the depth of slip surface are -13.39m and -13.37m under U_x and plastic zone mechanism, respectively. These two mechanisms have similar potential failure depths. According to the $\Delta\gamma_s$ method, the depth of sliding surface is -10.48m, which is nearly 3m larger than the other two results. Furthermore, the η value is approximately a half of the former (0.220/0.435=0.506), which shows that the load transfer factor is sensitive to failure mechanism.

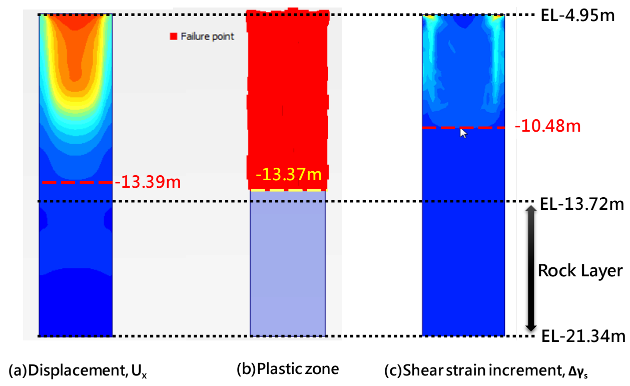

Fig. 4. Comparison of potential failure depth under different mechanism

Figure 5 presents the relationship between the depth of failure surface and the η value. The result shows that the η is proportional to the slip depth. In addition, when the depth of failure surface becomes larger, P_{up} increases more than P_{down} resulting in the increase of the η value.

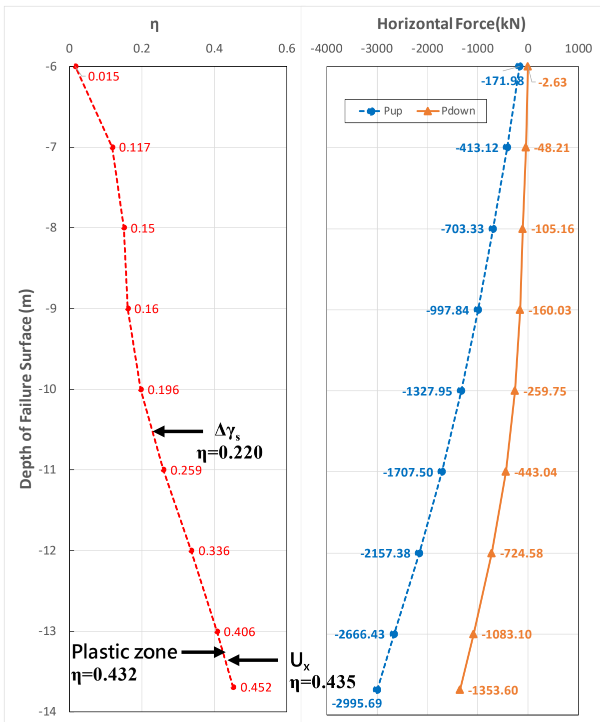

Fig. 5. Relationship between potential failure depth, load transfer factor and horizontal force

Additionally, several scenarios (ϕ=10°, 20°, 30°; c= 19, 48, 72 kN/m^2) were given to the aforementioned baseline model to examine the effects of soil strength parameters on η value. Based on the U_x mechanism, the η value is proportional to the soil cohesion but inversely proportional to the friction angle. This trend is roughly consistent with the analysis result of the $\Delta\gamma_s$ mechanism. Nonetheless, the η value of U_x mechanism is higher than the absolute η value of $\Delta\gamma_s$ mechanism (as shown in Figure 6). The main reason is that these two mechanisms lead to different depths of failure surface.

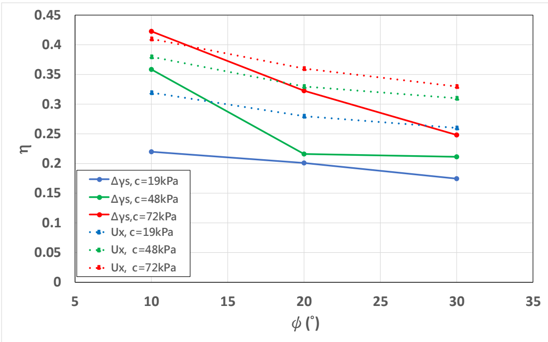

Fig. 6. Comparison of the load transfer factor under different mechanism ($\Delta\gamma_s$ and U_x)

Overall, regardless of failure mechanisms, the deeper the failure surface is, the higher the η value is under the higher c value. On the contrary, as the ϕ value of the slope becomes higher, the sliding surface of the slope becomes shallower and the η value turns lower (as shown in Figure 7).

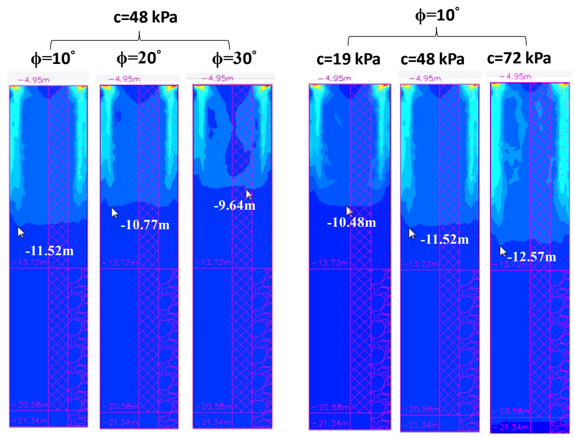

Fig. 7. Comparison of depth of potential failure under different c and ϕ using $\Delta\gamma_s$ method

5 CONCLUSIONS

Based on the analyses in this research, the conclusions and suggestions are as follows:

(1) The depth of failure surface obtained from shear strain increment ($\Delta\gamma_s$) is the shallowest. Moreover, the η value of shear strain mechanism is a half of the value of the plastic zone and the displacement mechanism. It shows that the failure surface mechanism has a great impact on the assessment of the soil arching effect.

(2) The impact of soil arching effect reduces with the increase of c value due to the deeper sliding surface. On the other hand, the depth of slip surface and the η value decrease with the increase of the ϕ value, which means the impact of the soil arching effect augments.

REFERENCES

Liang, R.Y. (2010). Field instrumentation, monitoring of drilled shafts for landslide stabilization and development of pertinent design method. Final Report for Ohio Department of Transportation, Report Number FHWA/OH-2010/134238.

Liang, R.Y. and Yamin, M. (2010). Three-dimensional finite element study of arching behavior in slope/drilled shafts system. International Journal of Numerical and Analytical Methods in Geomechanics,34(11), 1157-1168.

Liang, R.Y., and Zeng, S. (2002). Numerical study of soil arching mechanism in drilled shafts for slope stabilization. Soils and Foundations, Japanese Geotechnical Society, 42(2), 83-92.

Lin, H.D., Liang, R.Y., Tsai, P.H. and Dang, H. P. (2011). Analysis of load transfer factor of soil slope stabilized by drilled shaft. Proceedings, 3rd International Conference on Computational Mechanics (ISCM III), paper no. MS08-02, 222-223, Taipei.

Lin, H.D., Tjuar, R. and Dang, H.P. (2013). Analyses of drilled shaft effects on stabilizing the soil slope. Invited Paper, 1st Taiwan-Kazakhstan Joint Workshop in Geotechnical Engineering, Taipei, Taiwan.

Matsui, T. and San, K.C. (1992). Finite element slope stability analysis by shear strength reduction technique. Soils and Foundations, 32(1), 59–70.

Li, A.J, Merifield, R.S. and Lyamin, A.V. (2009). Limit analysis solution for three dimensional undrained slopes. Computers and Geotechnics, 36(8), 1330–1351

Li, A.J., Merifield, R.S. and Lyamin, A.V. (2010). Three-dimensional stability charts for slopes based on limit analysis methods. Canadian Geotechnical Journal 47(12), 1316-1334.

Qian, Z.G., Li, A.J., Merifield, R.S. and Lyamin, A.V. (2014). Slope stability charts for two-layered purely cohesive soils based on finite-element limit analysis methods. International Journal of Geomechanics, ASCE, 15(3), 06014022.

Lim, K., Lyamin, A.V., Cassidy, M.J. and Li, A.J. (2015). Three-dimensional slope stability charts for frictional fill materials placed on purely cohesive clay. International Journal of Geomechanics, ASCE, 16(2), 04015042.

Wei, W.B., Cheng, Y.M. and Li, L. (2009). Three-dimensional slope failure analysis by the strength reduction and limit equilibrium methods. Computer and Geotechnics, 36(1-2), 70–80.

Wei, W.B. and Cheng, Y.M. (2010). Stability analysis of slope with water flow by strength reduction method. Soils and Foundations, 50(1), 83–92.

Liu, J., Shang, K. and Wu, X. (2016). Stability analysis and performance of soil-nailing retaining system of excavation during construction period. Journal of Performance of Constructed Facilities, 30(1), C4014002.

Kelesoglu, M.K. (2016). The evaluation of three-dimensional effects on slope stability by the strength reduction method. KSCE Journal of Civil Engineering, 20(1), 229-242.

Cai, F. and Ugai, K. (2000). Numerical analysis of the stability of a slope reinforced with piles.", Soils Found, 40(1), 73–84.

Lin, H., Xiong, W. and Cao, P. (2013). Stability of soil nailed slope using strength reduction method. European Journal of Environmental and Civil Engineering, 17(9), 872-885.