Back Analysis of Support Force—A Case Study

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Abstract. Subsurface investigation for County Road 90 in Athens County, Ohio, indicated presence of reddish brown non-durable claystone bedrock of the Pennsylvanian aged Monongahela Group. The slope failure is an approximately 90 ft long slope section affected by landslide activity. The ground movement is associated with rotational type slope movement of fill and residual soil mass over the weathered bedrock surface. To remediate the landslide, a drilled shaft soldier pile cantilever retaining wall system was recommended. Ohio Department of Transportation recommends designing drilled shaft retaining wall based on guidance in their Geotechnical Design Manual. The force on the drilled shaft is calculated using the software program UA Slope to design the drilled shaft. In this article, the authors have compared the force generated on the drilled shaft with 2-dimensional model through the finite element shear strength reduction method (FEM) and back analysis of support force using a traditional limit equilibrium method (LEM). This paper will discuss the advantage of FEM and LEM methods to back calculate support force over UA Slope.

Keywords: Slope Stability Analysis · Limit Equilibrium · Finite Element

1 Introduction

Current landside inventory of Ohio Department of Transportation (ODOT) has over 10,000 sites, and new sites are periodically added as the slides are discovered. Drilled shafts are easier and faster to construct and avoid the need to address right-of-way issues, and most often used as a popular technique to stabilize unstable slopes. This type of structural element provides additional shear resistance for equilibrium, which leads to satisfactory stabilization of a slope. In order to resist a large lateral load imposed by a landslide, the permanent drilled shaft is closely spaced and has a typical diameter of 2 to 5 ft. For easier construction, large steel I-beams which can resist significant bending moments are used as typical reinforcement for drilled shafts.

Numerous methods have been developed for the analysis of drilled shaft reinforced slopes (Ito and Matsui 1975; Lee et al. 1995; Poulos 1995; Chen & Poulos 1997). When drilled shafts are utilized to stabilize the unstable ground, the pile design method plays an important role in ensuring stability and safety. There are several pile design methods, including the following:

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1. Limit Equilibrium method (LEM): This 2-dimesional analysis method involves dividing the slope cross section into slices, each of which is analyzed to determine whether it is stable or unstable. The forces acting on each slice, including the weight of the slice itself and any external loads, are compared to the resisting forces, which include the shear strength of the soil or rock defined using cohesion and/or frictional resistance. If the forces exceed the resisting forces, the slice is considered unstable and may contribute to a landslide.
2. Earth Pressure theory-based method: Coulomb Wedge earth pressure theories are used to calculate lateral pressures on drilled shafts (Peck et al., 1991). This method is used to estimate the lateral load on stabilizing piles located near the top of the slope, where a pavement needs protection and the slope below is allowed to move. This method does not consider slope stability failure mechanisms and does not satisfy the moment equilibrium.
3. Finite element analysis method (FEM): This method uses computer software to simulate the behavior of piles under various soil and loading conditions. Several authors (Carter et. al. 2000; Duncan 1999) presented the application of FE methods in slope stability problems.

ODOT has adopted the design of the drilled shaft for landslide stabilization based on the method developed by Dr. Robert Liang (Liang R. 2002; and Liang R.Y, 2010). Dr. Liang developed a software program called UA Slope that performs slope stability analyses for a specified shear surface and includes the effect of soil arching between single-row drilled shafts. The percentage of lateral load which passes between the shafts from the uphill soil mass to the downhill soil mass is a function of the soil strength, the drilled shaft diameter, the center-to-center spacing of the drilled shafts, the horizontal location of the drilled shafts on the slope, and the slope of the ground surface. The force generated by UA Slope then can be utilized to design the drilled shaft using the p-y method of analysis for the laterally loaded pile.

The main objectives of this study are to compare the lateral force on the drilled shaft due to movement of the surrounding soil using the Limit Equilibrium Method (LEM), Finite Element Method (FEM), Earth Pressure based method, and UA Slope; and provide recommendations for the selection of appropriate methods based on stability analyses.

2 Site Description

The studied site consists of stabilizing a landslide that has occurred along Strouds Run Road (CR 90) in Athens County, Ohio, United States (Fig. 1a). The project site is located within the Marietta Plateau region within the Allegheny Plateaus section of the Appalachian Plateaus physiographic province of Ohio. This region is characterized as a dissected high-relief plateau with mostly fine-grained rocks consisting of red shales, claystones, and siltstones. Landslides are also common, along with remnants of the ancient, lacustrine, clay-filled Teays drainage system.

A desktop study was performed to understand the geology of the area using Geological Survey Maps from the Ohio State Department of Natural Resources. The bedrock at the site is Pennsylvanian—aged, belonging to the Monongahela Group. The Monongahela Group consists of shale, siltstone, limestone, sandstone, and coal.

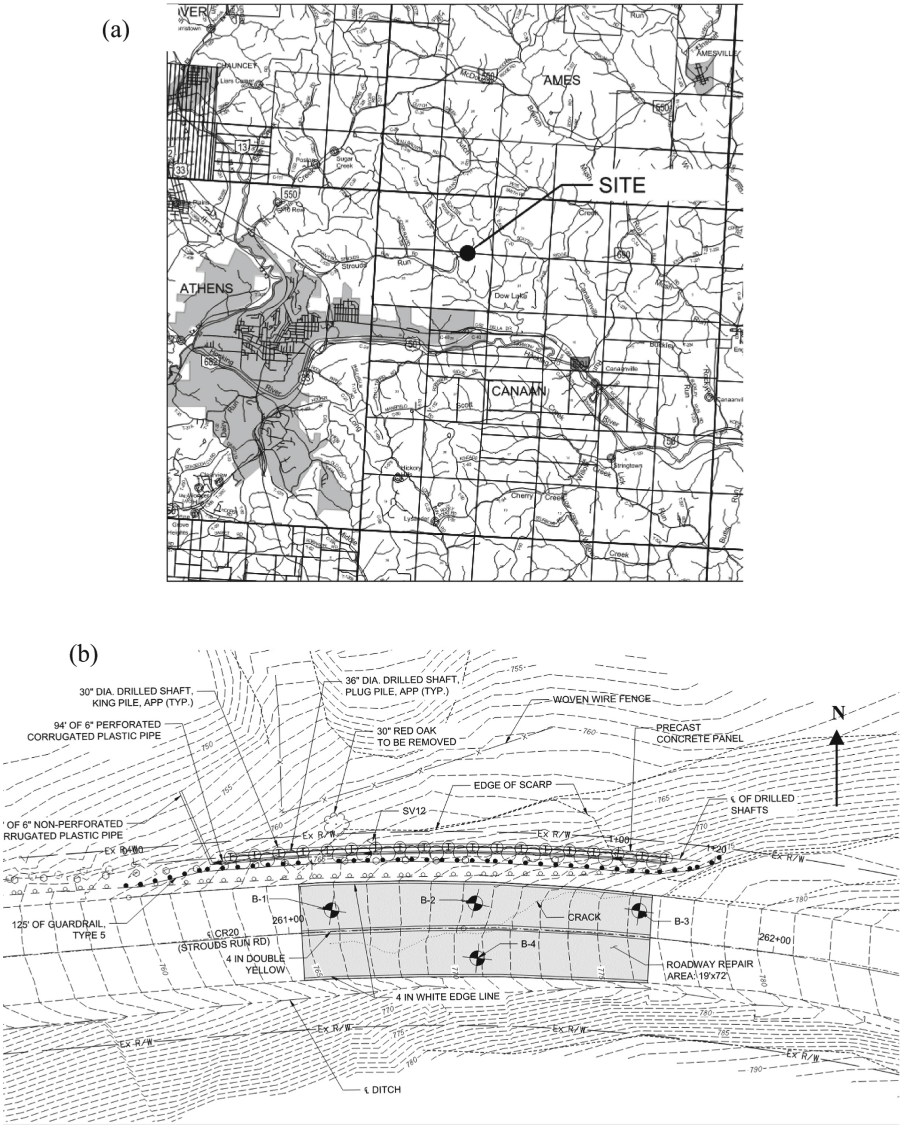


Fig. 1. (a) Site Location; (b) Site Topography

Four (4) borings were completed as part of the subsurface exploration (Fig. 1b). Borings B-1, B-2, B-3, and B-4 were drilled along the pavement edge and near the head scarp of the landslide area. The borings encountered fill and residual native soils to depths of about 2.5 to 26 ft below the existing ground surface underlain by sedimentary bedrock. The test borings extended to depths ranging from approximately 13 to 39 ft below the existing ground surface.

Underlying the pavement materials, fill soil was encountered, and consisted of very dense gravel and/or stone fragments with sand, very loose sandy silt, dense to very dense gravel and/or stone fragments with sand, silt and clay, and hard silt and clay. Fill soil was underlain by bedrock at Boring B-4.

Borings B-1 and B-2 encountered predominantly native cohesive soils such as soft to medium stiff silt and clay, and very stiff to hard silty clay overlying sedimentary bedrock. The native granular soil consisting of gravel and stone fragments with sand, silt, and clay was encountered in Boring B-2. The relative density of this layer was loose. Two samples had a liquid limit of 23, and plastic limits of 11 and 12. The moisture contents of the soil samples tested ranged from 5% to 22%. The borings encountered medium stiff cohesive soil from 5 to 15 ft below the existing ground surface, with a maximum moisture content of 22%. As the moisture content is the same as liquid limit, we assumed that a failure plan developed between 12 to 15 ft below the existing ground surface. It appears that the ground movement is associated with rotational type slope movement of fill and residual soil mass over the weathered bedrock surface. During our reconnaissance, we observed slope failure on the northwestern side of the roadway (Fig. 1b). The length of the landslide, measured roughly parallel to the roadway, was approximately 90 ft. The landslide resulted in a settlement of more than 4 inches of the existing roadway. More than half of the width of the existing roadway was affected due to landslide. The toe bulge was located approximately 33 ft away downslope from the edge of the pavement. The existing slope angles near the subject landslide area ranged from approximately 1.9 H:1V to 2.9 H:1V from the site topography map.

Sedimentary bedrock was encountered at a depth of about 2.5 to 28.5 ft below the existing surface at the test boring locations and consisted of claystone, shale, mudstone, and sandstone with severe to slight degrees of weathering. Rock Quality Designation (RQD) ranged from 0 to 88%. The unconfined compressive strength test results yielded strength ranges from of 509 to 4,433 psi.

Due to a roadway right-of-way limitation, a "Soldier Pile Cantilever" retaining wall was presented as most feasible recommendation for a remedial design to stabilize and protect the existing roadway from ongoing movement of the slope. The approximate location of the proposed Soldier Pile Cantilever wall alignment was assumed 5 ft away from the edge of pavement on the downslope side.

3 Slope Stability Analyses

Both two-dimensional (2D) limit equilibrium and finite element analyses were performed to evaluate the stability of the failed slope (Fig. 2). Based on the soil and rock descriptions, a simplified soil-rock model was developed.

Two sets of slope stability simulations have been studied in this paper. First, the soil friction angle for clay/slide mass was determined for failed slope (i.e., factor of safety (FOS) = 1.0, Fig. 2), and then the required stabilizing force must be determined to reach minimum FOS = 1.5. The LEM analyses were carried out using Spencer method and non-circular slip surface in the Rocscience SLIDE 9.0 software. UA Slope (Version 2.3) was also utilized to determine the load on the drilled shaft for critical failure surface using the LEM slope stability method.

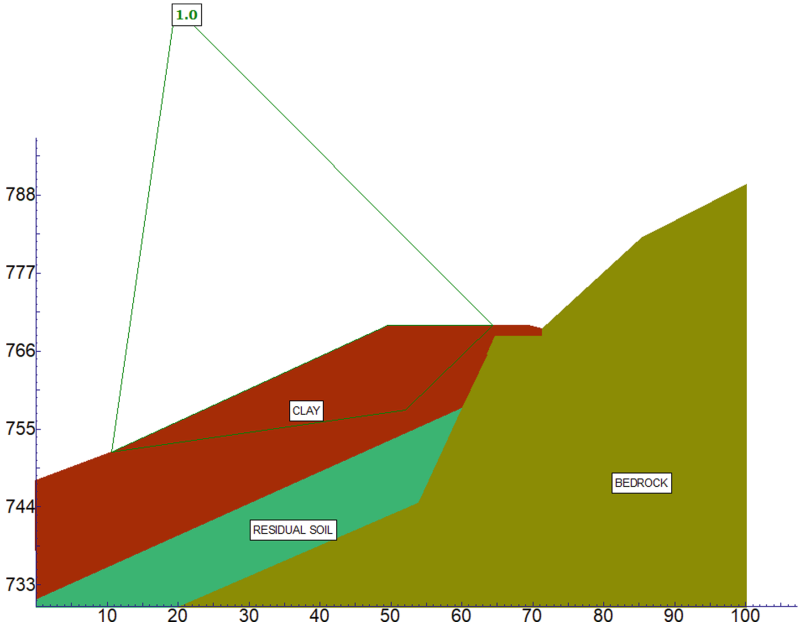


Fig. 2. Slope Geometry and Unconstrained Analysis of Slope

The finite element method (FEM) with the Shear Strength Reduction (SSR) (Griffiths and Lane 1999) is used to evaluate the lateral force on the drilled shaft. A strength reduction factor is applied to failure criterion (Mohr-Coulomb) for the matrix by reducing the shear strength. FEM simulations are carried out in 2D plane strain configuration using graded 6-node triangular elements. The poor-quality elements are prevented by specifying three criteria: i) ratio of (maximum side length)/(minimum side length) = 30; ii) minimum interior angle = 2 degrees; and iii) maximum interior angle = 175 degrees. The software Rocscience RS2 version 11.0 was used to perform the FEM analyses.

4 Material Properties

The behavior of the strain softening of soil was simulated using the elastic-perfectly plastic Mohr-Coulomb model. Initial element loading of all materials is “Field Stress and Body Force”. The initial stresses were established with an earth pressure coefficient of 1.0. Table 1 shows the soil and rock properties used for this study.

To conduct the back analysis of support force using the SLIDE program, the shear force (which needs to be determined), the length of the pile (which is 36 ft, approximately 10 ft embedded into bedrock according to ODOT Geotechnical Design Manual), and the spacing of the drilled shafts parameters were provided as suggested by Poulos (1995). After completing the unreinforced analysis, the required stabilizing force needs to be determined based on the LEM analysis. This shear force on the drilled shaft for different spacing was calculated from the stability analysis for the minimum factor of safety 1.5. The “Method A” was selected to determine shear force, as suggested by Duncan et al.

Table 1. Soil and Rock Properties

Type of Material	Unit Weight (pcf)	Friction Angle (degree)	Effective Stress Cohesion (psf)	Young Modulus (psf)	Poisson's Ratio
Clay	18	15	0	300,000	0.3
Residual Soil (Hard Clay)	128	26	200	2,000,000	0.3
Bedrock	145	32	1000	7,200,000	0.15

(2014). Method A uses the allowable force as the reinforcement force in the analysis, without dividing it by the factor of safety (FOS) that is calculated during the analysis. However, the soil strength is divided by the FOS that is determined in the slope stability analysis.

In RS2, the drilled shafts (Diameter = 2.5 ft) were modeled using a structural interface with a joint on either side of the reinforcement, allowing slip to occur between the reinforcement and the soil. The Timoshenko Beam formulation method was used to model the reinforcing piles as the standard beam liner type. As the drilled shafts were closely spaced, a contiguous reinforced piled wall was formed in the FEM analyses. The properties (thickness and elastic modulus) for the pile wall were determined using the method described by Lees (2013). The Poisson's ratio was fixed and set to 0.2 for the reinforced pile wall.

5 Results and Discussions

According to ODOT's Geotechnical Design Manual, if the slope below the stabilization drilled shaft is to be left without any modification and has a safety factor of less than 1.30, it must be considered unstable. In such a case, the analysis needs to account for the expected loss of passive resistance from the soil located downslope of the piles. The amount by which the ground surface needs to be lowered can be calculated using the following formula.

$$d_\tau tan\beta_{dh} \tag{1}$$

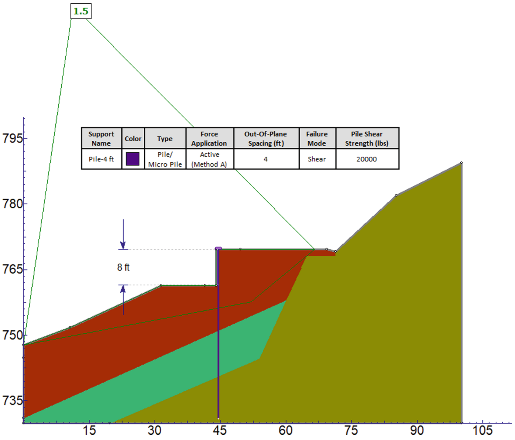
where

d_τ = depth to shear surface at the location of the drilled shaft
β_{dh}= angle of slope from horizontal

For slopes where β_{dh} = 45 degrees or steeper, the entire soil mass above the shear surface is neglected. To accomplish this, the back analysis involved reducing the ground surface elevation (approximately 8 ft), which effectively excludes the passive resistance between the actual ground surface and the artificially lowered ground surface from the analysis.

The drilled shaft will be designed for the reinforced analysis, assuming that the depth of shear surface is between 12 to15 ft below ground surface. For the analysis, the reinforced wall was located approximately 5 ft away from the edge of pavement assuming full mobilization of soil shear strength along the failure surface using SLIDE program. In RS2 analyses, the shear strength reduction was applied on upper 15 ft retained soil to determine the shear force on the drilled shaft due to slide soil movement. As the ground surface was artificially lowered on passive side, the downslope side soil was assumed stable. Hence, SSR was not applied for downslope side soil. The reinforced analysis for drilled shaft spacing of 4 ft is presented below (Fig. 3 and Fig. 4).

UA Slope is a reliable software tool for analyzing slope stability, but it has some limitations (Liang and Li, 2013). Unlike LEM slope stability programs such as SLIDE, UA Slope is not equipped to search for the critical failure surface. In order to generate



Support Name	Color	Type	Force Application	Out-Of-Plane Spacing (ft)	Failure Mode	Pile Shear Strength (lbs)
Pile-4 ft	🟪	Pile/ Micro Pile	Active (Method A)	4	Shear	20000

Fig. 3. Back Analysis of Support Force using SLIDE (Drilled Shaft Spacing is 4 ft)

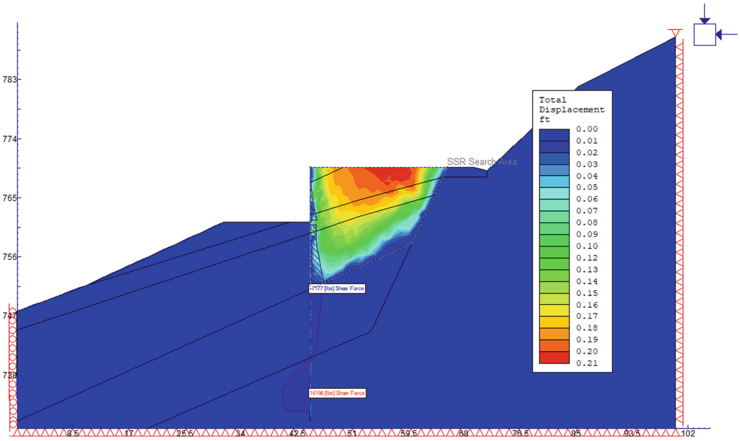


Fig. 4. Back Analysis of Support Force using RS2 (Drilled Shaft Spacing is 4 ft)

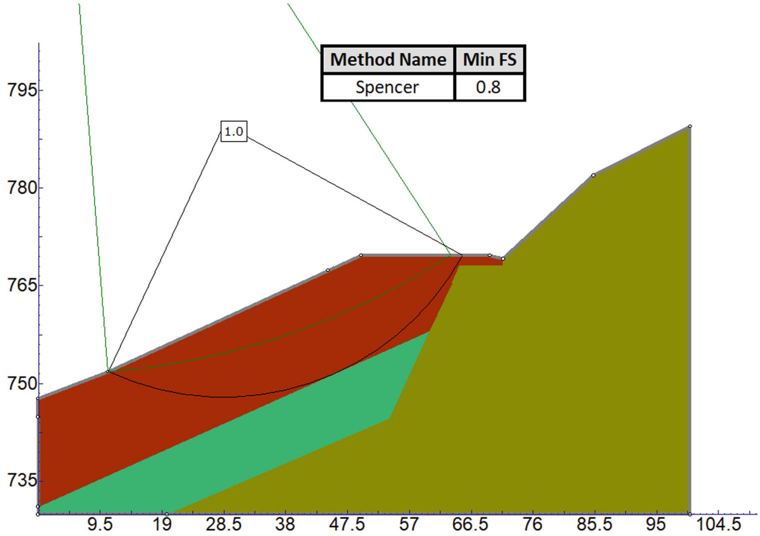


Fig. 5. Deepest Critical Failure Surface utilized for UA Slope Analyses

the maximum lateral force on the drilled shaft using UA slope, the deepest circular slip circle geometry from SLIDE analysis was used (Fig. 5). UA Slope considers the impact of soil arching between drilled shafts to calculate the shear force on the drilled shaft.

The support force from SLIDE, RS2 and UA Slope analyses were presented in Fig. 6. Furthermore, the traditional Wedge method was employed to determine the horizontal force acting on a drilled shaft. The outcomes demonstrated that the support force determined utilizing SLIDE was the smallest for drilled shaft spacing of 4 to 8 feet, as compared to the various other methods. RS2 evaluations revealed a support force that was 20 to 40% lower than that of the UA Slope when using drilled shaft spacing of 7 to 8 feet. The Wedge method indicated the highest support force for spacing of 4 to 5 feet in comparison to other techniques but showed a slightly lower support force for spacing of 7 to 8 feet compared to UA Slope evaluations.

The current version of the UA Slope program employed the force equilibrium procedure instead of using both force equilibrium and moment equilibrium procedures. The FOS of a drilled shaft slope system was calculated employing Method A, i.e., the reinforcement acts to decrease driving force. In this force equilibrium analysis method, the interslice forces are not known. Because the interslice forces are not known, Liang and Li (2013) assumes the distributed force between two slices is approximately similar to a triangular distribution instead of a uniform distribution. Hence, the interslice net force is at one-third height above the slice bottom. Because of the different assumptions employed in each method, and use of the deepest slip circle in the UA Slope program indicates generally higher support force compared to SLIDE or RS2 methods between 4 to 8 ft spacing of drilled shaft.

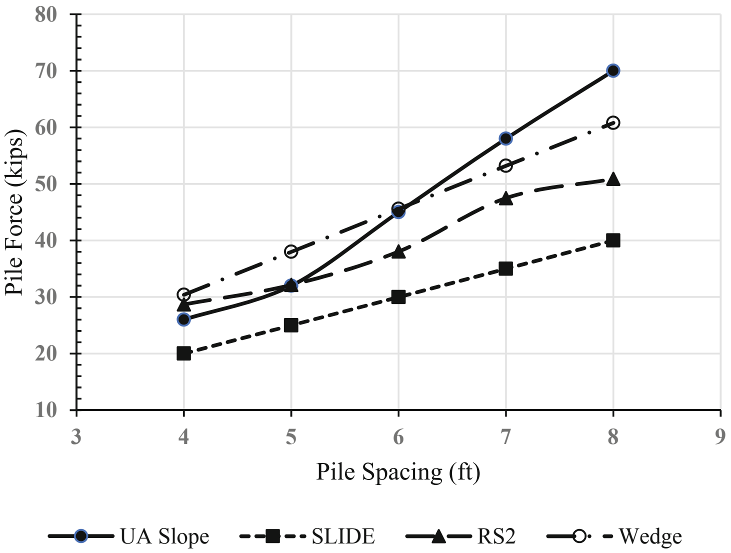


Fig. 6. Support Force Versus Spacing of Drilled Shaft Located 5 ft Downslope from the Edge of Pavement

6 Summary

In this study, the authors calculated the support force of the drilled shaft using LEM, UA Slope, Wedge theory, and FEM. The drilled shaft location was assumed within 5 ft from the edge of the pavement, and spacing between shafts was varied from 4 to 8 ft. The analyses indicated that the support force based on the UA Slope was typically higher than the SLIDE or RS2 method. The authors believe that the different methods have different assumptions, which is the primary reason for the variation in results. Hence, rigorous analyses should be performed using various numerical techniques. As the drilled shaft design for landslide stabilization is mainly governed by pile-head deflection at Service Limit State, a weighted average support force may be utilized for deflection analysis to provide a cost-effective design solution. However, a higher bound support force should be used for the factored Strength Limit State analysis.

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