DRILLED SHAFT LANDSLIDE STABILIZATION DESIGN

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This Geotechnical Bulletin (GB) is intended to provide guidance on design of drilled shafts for landslide stabilization. The most common method of remediation for an unstable existing slope consists of digging out the failed soil mass in a benched excavation and reconstructing the slope with compacted engineered fill, per GB2. However, in some situations with adverse slope geometry, limited right-of-way, or the failure of a river bank where the toe of the failure extends out into the bottom of the river, a structural solution must be employed. In this instance, drilled shafts can often be used to stabilize the existing unstable slope by embedding the shafts into a lower, stable stratum, preferably bedrock, and utilizing the mechanism of soil arching between the shafts to increase the nominal resistance against sliding to the point of stability. Where soil arching does not yield adequate resistance, a more robust structural solution such as a retaining wall may be necessary.

This bulletin contains guidance on all aspects of the design process, including landslide reconnaissance and exploration. This bulletin also contains a user’s guide for the University of Akron Slope Analysis Program, UA Slope 2.3, which is used in the Liang method analysis to determine the single shaft load for one row of evenly spaced shafts using soil arching for landslide stabilization. Additionally, this bulletin provides guidance for utilizing the program LPILE, developed by Ensoft, Inc., for design of drilled shafts reinforced with structural steel sections.

This bulletin and other information may be obtained from the Office of Geotechnical Engineering’s Web site (http://www.dot.state.oh.us/Divisions/Engineering/Geotechnical/). This Web site contains other ODOT Geotechnical documents and bulletins and has online copies of the Specifications for Geotechnical Exploration (SGE) and Geotechnical Engineering Design Checklists that are referenced in this bulletin.
A. SITE RECONNAISSANCE AND EXPLORATION

This section provides guidance for site reconnaissance, survey limits, exploratory drilling, and in-situ and laboratory testing of soil and bedrock for landslide remediation projects. Recommendations for installation of instrumentation, in the form of inclinometer casing and monitoring wells, are also provided. Subsurface exploration is a necessity for the analysis and design of a drilled shaft landslide stabilization solution. The analyses involved are quite rigorous, and the more data that is acquired; the more precisely the inputs can be estimated, and the more realistic the outputs will be.

1. Site Reconnaissance

a. Office Publication Search
Prior to making a site visit, endeavor to obtain as much knowledge about the geologic setting of the site as possible. A thorough search of various geologic, soil, and water resource publications can yield a large amount of information, which may provide greater insight to the probable causes and form of the landslide failure, and may immediately demonstrate which kinds of remediation options are possible and which kinds are not possible. See SGE Section 302.2, Office Reconnaissance, and the Geotechnical Engineering Design Checklists, Section II, Reconnaissance and Planning Checklist, for details and a list of publications recommended by the Office of Geotechnical Engineering.

b. Historic Geotechnical Data Search
In many cases, a landslide may have been explored in the past, one or more times. In some cases, a historic geotechnical exploration may have resulted in a remediation which subsequently failed. Such data can be helpful for planning a geotechnical exploration and for assessing feasible remediation alternatives. Historic boring logs add to the amount of available subsurface data, and mean that fewer new borings may potentially be required. An inventory of historic borings collected by ODOT is available from the Transportation Information Mapping System (TIMS) Geotech Map Viewer at the following location: http://gis.dot.state.oh.us/tims/Map/Geotech. Past recommended, designed, or constructed remediation schemes may also yield data which will be helpful in constructing a subsurface profile or in determining the reason for certain surface features. ODOT has collected an inventory of geohazards impacting the transportation infrastructure throughout the state, contained in the Geologic Hazard Management System (GHMS), a subset of the ODOT Geotechnical Data Management System (ODOT GeoMS), at the following location: http://ghms.odotgeoms.org/. Full rating information, and a history of past remediation work are available within the GHMS. Site locations and photos are also available within the TIMS Geotech Map Viewer.

Past project plans, either for the original construction of the roadway, a subsequent reconstruction, or for the construction of a remediation scheme, can also yield useful data. Cross sections will show both the historic “existing” ground profile, and the historic proposed ground profile, which can be compared to the existing ground line. This can show where soil or bedrock cuts or embankment fills were performed, and can help with determining which soils are fill as opposed to natural, virgin soils. Features from historic remediation schemes, such as rock buttresses, shear keys, benched excavations, and
rock channel protection (RCP) can yield helpful data for the construction of a subsurface profile.

c. Site Visit / Drilling Reconnaissance
Visit the site at least once, in order to gain a full understanding of the existing lay of the ground, evaluate the extent and severity of the landslide, and note surface features relevant to the geotechnical analyses. Include a drilling reconnaissance in the site visit, so that a geotechnical engineer may decide where drilling and installation of instrumentation should be performed, where there are obstacles to drilling access, and where drilling will be impractical. Also use this site visit to estimate the limits of the required site survey, and to make notes on particular features which the survey should locate.

Make a sketch of the site, and note all of the surface features which give evidence of the size, type, severity, and causes of the landslide. Figure 1 shows an example of a simple sketch of a typical landslide site, located along a river. We acknowledge that the toe of slope and limits of the slide are typically not known under water; however they are shown in this example for completeness. This example site will be used repeatedly throughout this bulletin.

![Figure 1: Example Landslide and Site sketch](image)

The following is a list of typical landslide features which are often present and should be noted:

Landslide “Anatomical” Features:
Head scarp
Toe bulge
Tension cracking
Hummocky ground
Bowed, leaning, or overturned trees
Leaning or overturned utility poles
Ditches, streams, and rivers, particularly if pinched by ground movement
Erosion features
Surface seepage or wet, soft ground
Unusually verdant or wetland vegetation

Roadway features:
   Longitudinal or transverse roadway cracking
   Dropped or uneven sections of pavement
   Deformed guardrail
   Closed off or pinched ditches
   Areas of pavement patching or “drag patching”
   Apparent limits of roadway cut or fill
   Rock cut slopes
   Existing and likely future impact of the slide on the roadway and traffic

Evidence of past remediation:
   Toe buttress
   Driven piles, pipes, or posts
   Retaining wall
   Rock buttress or RCP
   Drainage features

2. Site Survey
Establish the limits of the site survey during or immediately after the site visit. The sketch of the site created by the engineer is often useful to identify the area and features which the survey should locate, and it may be helpful to provide the surveyor with a copy of this sketch.

The following are minimum guidelines on the limits of the area to capture in the site survey:
   • 100 feet beyond the limits of the failure area, in all directions
   • 100 feet beyond the toe of the slope
   • Both right-of-way limits

Extend the survey beyond these minimums as necessary in order to capture additional relevant features, or to set the site in a more general context. Also, if the slide is on a river bank or at the edge of some other body of water, it is preferable to obtain soundings of the bottom of the water feature, out beyond the “toe of the slope,” where the bottom levels off.

Once the site survey is completed, develop a plan and profile, showing land usage and all pertinent topographical and geotechnical features, including right of way lines. Develop cross sections at a 25-foot interval along the roadway centerline (or at right angles to the movement of the slide, if the slide is not nearly perpendicular to the roadway). These cross sections will be used to develop a subsurface profile of the soil and bedrock, and to develop models for the stability analysis and Liang method analysis to determine shaft loadings.
3. Subsurface Exploration Program

Develop a subsurface exploration program which yields sufficient subsurface information to develop realistic subsurface profiles and models, but which is conservative and within reasonable limits for the available time and money. The historic geotechnical data search may find historic site borings which will yield useful data for planning additional borings or reduce the number of necessary new borings. See SGE Section 303.5.5 for general guidance on planning an exploration program for a landslide geohazard site.

a. Primary Borings

The most basic site exploration consists of drilling a single primary line of borings, in a cross section through the landslide. Perform enough borings such that the structure and slope of the soil strata and the bedrock surface may be determined. Figure 2 shows a plan view of the example landslide site again, with a proposed cross section of borings plotted through the slide. The following paragraphs will discuss the placement of the borings in this example.

Figure 2: Example Primary Exploratory Boring Cross Section

Boring B-001-1 has been placed at the approximate crest of the slope, on the outside shoulder of the road, near the head of the failure. This is an important location for a boring, and is sometimes the only location a boring can be obtained, due to access difficulties. Always attempt to put a boring in this location, and to get it within the area of the slide, if at all possible. The further downhill this boring can be obtained, the better, although this could require removing guardrail.
Boring B-001-0 has been placed across the road and uphill from boring B-001-1. Often, the only locations at which borings will be possible are at the approximate locations of borings B-001-0 and B-001-1. The combination of borings B-001-0 and B-001-1 will allow a determination of the slope of the bedrock under the roadway and upper slide area. If no borings are possible further downhill, we may have to use the boring data from these two borings and the existing ground surface to project and estimate a subsurface profile to the toe of the slide area.

Boring B-001-2 has been placed on the mid-slope. If there is a bench or nearly level area in the middle of the slope which is accessible to a drill rig, attempt a boring in this location. This will extend the knowledge of the subsurface information further down the hill, and allow a better projection or estimation of the subsurface profile. If it is possible to cut a path to the mid-slope with a bulldozer, with minimal disturbance to the slope, this may also be attempted. However, use caution with this method. It is likely to introduce further instability into the upper slide area, and quicken or worsen the failure, by cutting too deep of a bench into the side of the existing slope.

Figure 3: Example Exploratory Borings in Profile View

Boring B-001-3 has been placed at the toe of the slope. In this example, the boring is out in the river, drilled into the river bottom. If possible, a boring at the toe of the slope or toe of the slide area is desirable to complete the subsurface profile. However, this is often not possible. Even when the slide is not on the bank of a river, the toe of the slope may be inaccessible to drilling equipment. If the slide extends into a body of water, a boring off of a floating platform, or barge, may be attempted at the toe. If a barge is not available, it may be possible to drill a boring at the edge of the water. Regardless, the more subsurface data which can be obtained along the cross section with the primary borings, the better. The proposed borings for this example are shown in profile view in Figure 3.
b. Secondary Borings
It is desirable to obtain additional borings up- or down-station (transverse to) to the primary boring cross section. These are helpful to define the limits of the slide area, to further refine the subsurface data, and to define the slope of the bedrock surface transverse to the direction of the slide. A better understanding of the top of bedrock across the site is especially helpful when planning the construction of drilled shafts.

If the landslide is very wide transverse to the direction of movement, or is composed of a number of smaller slides along a length of roadway, it is also prudent to drill more borings along additional “primary” boring cross sections. Each of these cross sections may be individually analyzed, to locate the most critical cross section or to further refine the remediation design.

c. Soil and Bedrock Sampling
When drilling and sampling for subsurface exploration of a landslide, continuous soil sampling should be performed, per SGE Section 303.5, Boring Type C, Geohazard Borings. Perform undisturbed (Shelby tube) sampling whenever soft or very soft cohesive soils are encountered, and at the depth of the shear failure surface, if this is known. If auger refusal or SPT refusal in bedrock is encountered, take a core of the bedrock.

d. In-situ Testing / Instrumentation
Most soil samples will be obtained by split spoon with the Standard Penetration Test (SPT) method, which will give a rough estimate of the soil consistency or density. Also perform a pocket penetrometer reading on cohesive soil samples, in order to obtain a second data point to determine the consistency and unconfined compressive strength. Exploration with Cone Penetrometer Testing (CPT) may also be performed in tandem with the drilling and soil sampling, in order to obtain a better estimate of the soil strength, and often to read the pore water pressure as well. In bedrock, a pressuremeter or dilatometer may be used to obtain an in-situ evaluation of the bedrock strength and stress-strain behavior.

Inclinometer casings are very often installed in landslide exploratory borings in order to determine the depth of the shear failure surface, and to obtain a better estimate of the rate and severity of the shear failure. The most advantageous location at which to install inclinometer casing is at the approximate center of the sliding mass. If the location of the head scarp and toe of the slide are known, determining the depth of failure at the center of the slide will give a good approximation of the shape of the entire failure surface. More than one inclinometer installation along the primary boring cross section can further refine the data. In the example shown in Figure 2 and Figure 3, inclinometer installations have been made at boring locations B-001-1 and B-001-2. Inclinometer installations in secondary boring locations or borings outside of the visible slide area are less critical, but may serve to define the size, shape, severity, and limits of the shear failure.

Ground water monitoring wells or piezometers may also be installed in the landslide exploratory borings, to determine the approximate level of the water table. Elevated ground water is often a major contributing factor in landslide failures, and determining the shape and depth of the “static” ground water surface will aid in modeling the existing conditions. Do not cluster inclinometer installations and ground water monitoring wells in
the same borings. If a side-by-side installation is desired, drill an offset boring for the second instrumentation installation.

Geophysics have also been found useful with a good level of success to determine the top of bedrock, and with some success to delineate the shear failure surface itself. In this event, typically run one or more lines up and down the slope through the failure area and/or along the proposed alignment of the drilled shaft retaining structure. Survey the slope cross section to be profiled, and determine the elevation of each probe or geophone. Geophysics may not be successful in every situation, particularly if the top of bedrock is relatively deep, there are dense soils above bedrock that make a contrast difficult to determine, or if there is a large amount of background noise that may mask the signal being collected by the particular methodology in use. Geophysical methods should always be supplemented and confirmed by borings performed within the geophysical survey line.

e. Laboratory Testing of Soil and Bedrock Samples
The laboratory testing program for a landslide exploration should generally be more rigorous than the programs for either a roadway subgrade exploration or a structure foundation exploration. Firstly, the number of soil samples is typically greater per boring, and additionally, we desire a greater refinement in the soil classification and shear strength determination. Classification testing of the soil aids in determining soil stratification for the subsurface profile. Moisture content testing aids in determining the ground water level. Undisturbed soil samples can be tested for unit weight and shear strength, which aid in determining engineering properties of the soils for the stability analysis modeling.

Subject all soil and bedrock samples to visual classification per SGE Section 602, and group them by similar classifications into preliminary strata. Subject at least one sample per stratum, per boring, to mechanical soil classification per SGE Section 603. Subject all undisturbed soil samples to unit weight testing, and subject samples near the failure surface to shear strength analysis by either unconfined compressive strength, unconsolidated-undrained (UU) triaxial compression, consolidated-undrained (CU) triaxial compression, or direct shear testing per SGE Section 604. Describe all bedrock samples per SGE Section 605. Intact bedrock cores may be subjected to unconfined compressive strength testing per SGE Section 606.

f. Boring Logs
Generate boring logs for every boring, per SGE Section 703.3, with visual descriptions of all soil and bedrock strata, and showing all available data from the exploratory borings, in-situ testing, and laboratory testing of the soil and bedrock samples. Also generate a Soil Profile - Landslide, per SGE Section 704, with graphic boring logs, and at least one cross section view per primary boring cross section.

B. SOIL AND BEDROCK PROFILES

Generate a subsurface profile of the soil and bedrock for each primary boring cross section at which modeling and analyses are to be performed. Combine soil and bedrock information from the subsurface exploration and laboratory testing, as shown in the boring logs, with the cross
sections from the site survey and any historic data to build as realistic a representation of the subsurface conditions as possible.

1. Identification of Soil and Bedrock Layers
Group soil samples across the subsurface profile into a finite number of discrete strata, so that modeling of the subsurface conditions can be performed for stability analyses. Lay the graphical boring logs on top of the site survey cross section along the axis of the primary borings, or the cross section views from the Soil Profile - Landslide may be used. Analyze all of the soil samples, comparing factors such as visual and mechanical classification, color, plasticity, gradation, SPT blow count, water content, and undisturbed laboratory test results, in order to group these samples into logical units which will define soil strata. Pay attention to the depositional environment of the site, apparent areas of cut and fill, exposed bedrock faces, and past construction plans, to add to the boring data and further aid in identifying the various strata. Figure 4 shows the subsurface profile for the example problem introduced in Section A.

![Figure 4: Example Soil and Bedrock Subsurface Profile](image)

Also identify the top of bedrock in each boring across the subsurface profile. Make a distinction between weak bedrock, “competent” bedrock, and strong bedrock.

Generally, the top of weak bedrock will correspond with the depth at which SPT blow count refusal (greater than 50 blows per 6”) is reached, but where exploratory borings can still be advanced by soil auger. This rock will typically have a relative strength of very weak to weak, with an unconfined compressive strength in the range of 200 psi to 1500 psi. Weak bedrock is often highly weathered or broken, with a low RQD. Weak bedrock, by this definition, is sometimes also called “Intermediate Geomaterial.”
The top of competent bedrock will roughly correspond with the depth at which auger refusal is reached, and at which further bedrock sampling must be done by diamond-tipped core bit. This rock will typically have a relative strength of slightly strong to moderately strong, with an unconfined compressive strength in the range of 1500 psi to 7500 psi. Competent bedrock is often slightly to moderately weathered.

Strong bedrock may be slow and difficult to core, and is important to note for constructability reasons. This rock will typically have a relative strength of strong to extremely strong, with an unconfined compressive strength greater than 7500 psi. This rock is usually unweathered to slightly weathered.

2. Estimate Soil Engineering Properties

Estimate the engineering properties of the soil strata in order to model the subsurface profile for stability analyses. Interpret these values directly from the results of undisturbed soil testing, or provide estimates through engineering judgment and experience using the results of soil classification testing and SPT blow counts.

Table 1 provides estimates for the unit weights of cohesive and granular (cohesionless) soils based on SPT blow count and depth of the soil sample. The values in Table 1 are based on the engineering experience of the author, and are useful as a first approximation for unit weight to be used in stability analyses, where unit weight testing of the soil has not been performed.

<table>
<thead>
<tr>
<th>TABLE 1 – Typical Unit Weight Relationships for Various Soils</th>
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<tr>
<td>All unit weights in this table are expressed in pounds per cubic foot (pcf).</td>
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<tr>
<td>Properties for Cohesive Soils</td>
</tr>
<tr>
<td>Consistency</td>
</tr>
<tr>
<td>Very Soft</td>
</tr>
<tr>
<td>Soft</td>
</tr>
<tr>
<td>Medium Stiff</td>
</tr>
<tr>
<td>Stiff</td>
</tr>
<tr>
<td>Very Stiff</td>
</tr>
<tr>
<td>Hard</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Properties for Granular Soils</th>
<th>Unconfined Compressive Strength qu*</th>
<th>Dry Unit Weight / Wet Unit Weight at Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>Blow Counts N&lt;sub&gt;60&lt;/sub&gt;</td>
<td>tsf</td>
</tr>
<tr>
<td>Very Loose</td>
<td>0 - 4</td>
<td></td>
</tr>
<tr>
<td>Loose</td>
<td>4 - 10</td>
<td></td>
</tr>
<tr>
<td>Medium Dense</td>
<td>10 - 30</td>
<td></td>
</tr>
<tr>
<td>Dense</td>
<td>30 - 50</td>
<td></td>
</tr>
<tr>
<td>Very Dense</td>
<td>&gt; 50</td>
<td></td>
</tr>
</tbody>
</table>

* Granular (cohesionless) soils cannot, by definition, exhibit a meaningful value for unconfined compressive strength.

Estimate the angle of internal friction (ϕ) and cohesion (c) of the soils as appropriate for a long-term (drained) stability analysis. Similarly to Table 1 for the unit weight, Table 2 provides
estimates for the drained internal friction angle ($\phi'$) and cohesion ($c'$) of cohesive and granular (cohesionless) soils based on SPT blow count, consistency, and density. The values given in Table 1 and Table 2 are approximations, derived from SPT blow counts. It should be noted that the Standard Penetration Test yields highly variable results, and gives a poor approximation of the strength of cohesive soils, or soils which have a large amount of gravel or larger particles. These values provide a fair first estimate of the soil engineering properties; adjust these as necessary to fit the observed existing conditions and the results of stability analyses.

<table>
<thead>
<tr>
<th>Properties for Cohesive Soils</th>
<th>&quot;Typical&quot; Long-Term Strength Values</th>
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</thead>
<tbody>
<tr>
<td>Consistency</td>
<td>Blow Counts N&lt;sub&gt;60&lt;/sub&gt;</td>
</tr>
<tr>
<td>Very Soft</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>Soft</td>
<td>2 - 4</td>
</tr>
<tr>
<td>Medium Stiff</td>
<td>4 - 8</td>
</tr>
<tr>
<td>Stiff</td>
<td>8 - 15</td>
</tr>
<tr>
<td>Very Stiff</td>
<td>15 - 30</td>
</tr>
<tr>
<td>Hard</td>
<td>&gt; 30</td>
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<tr>
<td>Dense</td>
<td>30 - 50</td>
</tr>
<tr>
<td>Very Dense</td>
<td>&gt; 50</td>
</tr>
</tbody>
</table>

3. Locate Ground Water Surface

Determine the ground water surface in the subsurface profile for representation in the stability model. In some instances, complex hydrogeologic conditions may exist, such that there is not one single ground water table with dry or moist soils above and saturated soils below. However, in most cases, a single ground water surface may be approximated. In the subsurface, the ground water surface may be located fairly accurately at single points through long-term observations with ground water monitoring wells. Short-term observations (made during drilling) are often inaccurate, due to low permeability limiting the rate of water level recharge in the open boring hole, caving of soils from the walls of the open boring hole displacing free water, and the use of drilling fluids. However, short term observations may give a clue about the range of depths at which the ground water surface lies, and sometimes, fairly accurate observations of the depth at which water was “first encountered” will be made. Water contents of the soil samples may also provide data to estimate the depth to the ground water surface.

Utilize knowledge of hydrogeology and subsurface flow to connect the ground water surface between known points. The ground water surface should intersect with free water at the ground surface, and should slope downwards with a realistic potentiometric surface, generally following the lay of the land. If bedrock is shallow, the ground water surface often coincides with the top of bedrock. Figure 5 shows the ground water surface in the subsurface.
If the landslide was triggered or aggravated by a rapid drawdown event, or if a rapid drawdown event is likely to occur at the site in the future, also perform the analyses for a ground water surface in the rapid drawdown condition. For example, such an event occurred on the Ohio River, above the Belleville Lock and Dam, in January and February 2005, when runaway barges were caught in the flood gates of the dam. To construct a ground water surface for a rapid drawdown event, the normal pool elevation, the flood elevation, and the rapid drawdown elevation (if different than the normal pool) of the river should be known. River gaging stations along most major waterways provide a useful historical record of the river level during flood events. If flood data cannot be found, a conservative estimate is to assume the flood water reached the crest of the failing slope. The exact subsurface level of the ground water cannot be known, unless ground water monitoring wells were already in place before the flood event, and readings were taken during the flood, but nevertheless, it is possible to approximate a reasonable potentiometric surface, similarly to the normal ground water condition. In this case, however, the ground water surface will remain nearer to the existing ground surface, and will probably meet the ground surface somewhere in the mid slope. The ground water will typically continue at ground surface level down to the free water level below. Figure 6 shows an example of a rapid drawdown condition ground water surface in the subsurface profile.
4. Estimate Shear Failure Surface

Before conducting a stability analysis, estimate the shear failure surface using engineering judgment and experience. Review the subsurface profile, inclinometer data, and landslide features noted in the site reconnaissance and site survey, and construct a realistic representation of the shear failure surface which fits with the available evidence. This failure surface is merely an approximation, based on the engineer’s interpretation of the mode of failure, but it should provide a useful starting point, and will give a metric with which to compare the results of computerized stability analyses, to determine whether the outputs seem reasonable.

In constructing the estimated shear failure surface, make sure it intercepts the ground surface at the head scarp and toe bulge (if evident), and make sure it conforms to the inclinometer data showing the depth of shear failure. If the bedrock is steeply sloping beneath the hillside and relatively shallow compared to the size of the failure, consider the likelihood that the failure surface intersects or travels along the top of rock. Highly weathered residual material at the top of the bedrock surface will often make up a thin, weak layer that provides a path of least resistance where a shear surface can develop.

If the toe of the landslide is in a river or other body of water, and is not visible from the ground surface, the engineer must use the other available data to project the failure surface out to its toe. Hopefully, soundings of the bottom of the waterway have been obtained. Depending on the detail and resolution of the soundings, the toe bulge may be apparent on the cross sections. Otherwise, if the toe of the slide is not readily apparent, consider projecting the failure surface out to the natural toe of the slope. Unless there is some bearing capacity failure which makes the underlying material too weak to hold up the hillside above (unlikely
in a natural setting where the slope has existed for a long time) the failure is likely to meet the ground surface at the natural toe of the slope.

Figure 7 shows the estimated shear failure surface for the example problem. The inclinometer at boring B-001-1 showed a shear failure at approximately 20 feet deep, near the bottom of the “clayey alluvium stratum,” and the inclinometer at boring B-001-2 showed a shear failure at approximately 28 feet deep, near the top of rock. The estimated shear failure surface has been connected between these two points and the head scarp visible at the ground surface, and has then been projected along the top of rock. Although a small bulge at the toe is evident, this is at the bottom of the river, and was not visible during the site visit. The bottom of the river was surveyed through soundings, but the resolution of this survey is not high enough to be sure of a toe bulge feature. Therefore, the estimated failure surface has been projected to the toe of the slope, where the river bottom levels off.

![Figure 7: Estimated Shear Failure Surface in Subsurface Profile](image)

C. StABILITY ANALYSIS

Perform a computerized limit equilibrium stability analysis of the existing condition, using a model based on the subsurface profile developed along the primary boring cross section. Initially use estimated shear strength and unit weight values for each of the subsurface profile strata similar to the recommended values from Table 1 and Table 2. Refine these values during the analysis, through “back-calculation” of the engineering properties.

If the shear failure surface is estimated to move along the top of rock, add a new “soft rock” layer along the surface of the top of rock, through which a shear failure surface will develop. Through experience with many slides of this type, we have found that there is often a thin, weak boundary zone along the top of rock, with very low shear strength. This layer is often not identified in
borings. Even when identified, this layer is typically not revealed as “soft” by vertical exploration and sampling methods such as SPT, but it exhibits residual strength properties due to historic landslide movement. OGE recommends representing this zone as a two-foot ± thick layer of very soft cohesive soil, with little to no cohesion, and an angle of internal friction usually between 12° to 18°.

The calculated shear failure surface that is output by the analysis should have a Factor of Safety of 1.0, and should roughly coincide with the estimated shear failure surface or with the known points of shear failure, as given by the head scarp, inclinometer data, and toe bulge. If the initial run of the analysis does not meet these criteria, adjust the engineering properties of the soil until the computerized analysis produces an output which conforms to these conditions. Assuming the slide event was triggered by excess pore water pressures within the slope, it may also be prudent to raise the piezometric surface above that for the static condition or that revealed by monitoring wells post-failure. Typically, a combination of both (adjusting soil properties and piezometric surface) is performed. Figure 8 shows the output of the computerized stability analysis for the example problem in the existing condition utilizing GeoStudio 2018 R2 Slope/W. Note that a thin “Soft Rock” layer has been added to the top of the bedrock surface.

Figure 8: Computerized Stability Analysis

Do not include an artificially curved “layer” of residual failed soil which mimics the estimated failure surface. Such a layer will force development of the failure surface by the computerized analysis along the new layer. However, it will inaccurately predict the Factor of Safety for other
portions of the slope, and for a reconstructed or retained slope. This method of artificially forcing the failure surface also inaccurately predicts the loading on drilled shafts per the Liang method Analysis. We are interested in the reasons for the initial development of the shear failure, and in preventing similar such failures. Therefore, we wish accurate modeling of the entire slope and all strata for “pre-failure” conditions, so that we can see development of the failure surface along the expected path, and hopefully predict other likely failure surfaces, especially post-remediation. We acknowledge that the soil shear strength along the failure surface is lowered to residual strength values once the failure occurs and substantial movement has taken place. However, we would rather modify the strength of all of the soil strata and the level of the water table until an approximation of the initial failure conditions are achieved so that we can protect against any future such failures.

D. Liang method Analysis

Dr. Robert Liang of the University of Akron published two papers, one in December, 2002, titled “Drilled Shaft Foundations for Noise Barrier Walls and Slope Stabilization,” and one in November, 2010, titled “Field Instrumentation, Monitoring of Drilled Shafts for Landslide Stabilization and Development of Pertinent Design Method,” as part of the results of a research project conducted for the Ohio Department of Transportation. The goal of this research was to develop a methodology for design of drilled shafts to stabilize unstable slopes. This research built upon the results of two earlier research projects by Dr. Robert Liang and Sanping Zeng, “Numerical Study of Soil Arching Mechanism in Drilled Shafts for Slope Stabilization,” and “Stability Analysis of Drilled Shafts Reinforced Slope.” These research projects used two-dimensional finite element modeling as well as centrifuge testing of physical models to study the effects of soil arching between pairs of equally spaced, laterally loaded drilled shafts in a single row. As a result of these research studies, Dr. Liang developed a mathematical model to predict the percentage of lateral load from the soil which is transferred to the shafts as opposed to the percentage which is passed between the shafts. The percentage of lateral load which passes between the shafts from the uphill soil mass to the downhill soil mass, the “Load Transfer Factor” (η), is a function of the soil cohesion (c), the soil angle of internal friction (φ), the drilled shaft diameter (D), the center-to-center spacing between the drilled shafts (S), the location of the drilled shafts on the slope (ξ) and the angle of steepness of the slope from horizontal (β). The two factors relating to shaft geometry, S and D, are typically expressed as a spacing-to-diameter ratio (S/D). We refer to this analysis methodology as the Liang method.

A computer program called UA Slope 2.3 was developed as part of the “Field Instrumentation, Monitoring of Drilled Shafts for Landslide Stabilization and Development of Pertinent Design Method,” and the subsequent “Enhancement of UASLOPE for Improving Implementation Efficiency” research studies. This program uses inter-slice forces from the method of slices for slope stability calculation, together with the results of the mathematical model for η, to calculate the force imposed on one shaft in a single row of equally spaced drilled shafts by a moving soil mass above an assumed soil shear failure surface. The failure surface is either estimated or determined by a stability analysis per Section C. The UA Slope 2.3 program requires as its inputs the geometry of the ground surface and soil strata, the geometry of the shear failure surface, the geometry of the phreatic surface, the physical properties (cohesion, friction angle, and unit weight) of each soil stratum, and the drilled shaft geometry (offset location, diameter, and spacing). A user’s manual for UA Slope 2.3 is attached as an appendix. The user's manual
fully describes how to input data and run the program, however, some of the major points will be
reiterated and expanded upon in this section.

Firstly, it should be noted that the geometric origin for all data input in the UA Slope 2.3 program
is at the top left, and the slope must always be represented from uphill on the left to downhill on
the right. In other words, all geometric data is entered in X,Y coordinates, where 0,0 is at the
top left, X increases from left to right, and Y increases from top to bottom.

Also, the geometric data for the UA Slope 2.3 program must be input in vertical slices. Each soil
stratum (including the ground surface) is defined by points along its top, where it intersects each
vertical slice. The maximum number of vertical slices is 50, and these include the boundaries
at the right and left limits of the represented cross section. Therefore, depending upon the
complexity of the geometry, the vertical slices must be chosen with care in order to represent
each change in geometry along the top of each stratum. Strata must be input from top to bottom,
and must be represented across the entire cross section, whether they extend all the way across
or terminate somewhere in the middle. Wherever a layer terminates, the coordinates defining
its top surface will be the same as those for the layer below – in other words its thickness will be
zero. The maximum number of layers is 30. One extra layer – which does not count in the
maximum number of soil layers – is always input, defining the bottom of the lowest layer. This
bottom layer must be flat, with the same Y-coordinate all the way across the cross section.

The coordinates defining the ends of the shear failure surface must exactly meet with the ground
surface, or the program will output an erroneous Factor of Safety. We recommend that vertical
slices should be positioned at the end points of the shear failure surface, so that the ground
surface coordinates and the shear surface end coordinates may coincide at these points. The
points defining the shear failure surface do not otherwise have to be on the vertical slices, and
points in-between vertical slices will usually need to be entered in order to properly define the
shape of a curving failure surface. However, we recommend that wherever the failure surface
intersects a vertical slice, this should be represented by an input point. The UA Slope 2.3
program allows a maximum of 50 points to define the shear failure surface.

Similarly, the points defining the phreatic surface do not have to be on the vertical slices, and it
will often be advantageous to enter points in-between vertical slices to properly define the shape
of the phreatic surface. However, the phreatic surface needs to extend across the entire cross
section, from the first to the last vertical slices, which are the boundaries at the right and left
limits of the represented cross section. The UA Slope 2.3 program allows a maximum of 50
points to define the phreatic surface.

We recommend that a geometric model of the analysis cross section be built in a CADD drawing,
with each vertical slice drawn in, and all the intersections between the slices and strata
determined before attempting to input the data into the UA Slope 2.3 program. Building a
geometric model will also allow determination of all the points to define the shear failure surface
and phreatic surface. We also recommend entering all the coordinates into a spreadsheet or
similar matrix, to consult while entering the data into the UA Slope 2.3 program. This will limit
the number of data entry errors.

Figure 9 shows the geometric model constructed for the example problem. This model has
twelve vertical slices, including the left and right boundary limits. Note that the “Fill,” “Colluvium,”
“Clayey Alluvium,” and “Residuum” layers do not extend all the way across the model. Where the “Fill,” “Colluvium,” and “Clayey Alluvium,” layers terminate on the right, their defining coordinates become the same as the ground surface for the rest of the width of the model. Where the “Residuum” layer terminates on the left, its coordinates become the same as the “Soft Rock” layer below. Note also that the geometric model constructed for UA Slope 2.3 is not as wide as the model constructed for stability analysis (as shown in Figure 3 through Figure 8; it is not necessary to make the UA Slope 2.3 model any wider than the limits of the shear failure surface.

![Figure 9: Geometric Model with Vertical Slices](image)

The UA Slope 2.3 program requires the input of three engineering soil properties per stratum, cohesion, friction angle, and total unit weight. The cohesion and friction angle for each stratum should be approximately the same as those utilized in the computerized stability analysis. However, the unit weight must be approximated to a single value for each stratum. We recommend utilizing the moist unit weight for those strata entirely above the phreatic surface, and we recommend utilizing the saturated unit weight for those strata entirely below the phreatic surface. If the phreatic surface passes through a stratum, we recommend selecting a unit weight somewhere in-between the moist and saturated unit weights, based on the relative percentage of the stratum which is above or below the phreatic surface.

After the UA Slope 2.3 program is started for the first time, or if **File, New** is selected from the drop down menus, the Main Menu screen will open, with “UA Slope Program Version 2.3 – Untitled” displayed on the title bar. Figure 10 shows the UA Slope 2.3 program Main Menu. The Main Menu screen is the only screen in the UA Slope 2.3 program; all data is input on this screen, the program is executed from this screen, and program outputs appear on this screen. The
The program also has four drop-down menus, for file functions, program execution, program options, and “Help” information about the program. The Options drop-down menu will display two small dialogue boxes for changing file paths (most of which should not be changed or the program will cease to function) and for Chart Options, which allows the user to change the colors used in the “Chart” graphic that appears in the upper right corner of the Main Menu screen. It should be noted that, by default, the program only has colors defined for 7 soil layers: if your model has more layers than this, the additional layers will change colors randomly every time the mouse scrolls over the Chart, which can become visually bothersome. Therefore, we recommend assigning colors to at least as many layers as you will have in your model.

Before beginning to input data, the user must input the units of measurement (English or Metric), number of vertical sections, and number of soil layers. The user must also select the analysis method as either total stress method or effective stress method. We recommend using the effective stress method, as the load transfer factor equation coded in the program was based on effective stress concepts, and is not calibrated or verified for total stress analysis.

Pore Pressure Options, on the lower right of the Main Menu, allows the option to select “No Pore” pressure, “Constant Ratio” pore pressure, or “Specified Phreatic” surface. No pore pressure does not take into account pore water pressure effects, constant ratio pore pressure applies the same pore pressure effect to every slice in the method of slices analysis, and specified phreatic surface allows the user to define a ground water table to set the effect of pore water pressure on the analysis. We recommend utilizing the specified phreatic surface, as this is the most realistic alternative.
The problem geometry for the Slope Profile Vertical Sections, Specified Phreatic surface, and Slip Surface are input into spreadsheet-like grids. The X-coordinates are entered on the top row, and Y-coordinates are entered on each lower row, corresponding to each X-coordinate for each surface. The number of Slope Profile Vertical Sections and Soil Layers are specified as mentioned above on the upper right portion of the Main Menu screen, and their selection will automatically format the Slope Profile Vertical Sections grid for the appropriate number of entries. To select the number of points for the Specified Phreatic surface and Slip Surface, right-click with the mouse pointer in the box containing the grid, and select either Add Point, Set Points, or Delete Point. For the Set Points option, a second small dialogue box opens: the user should type the number of points in the dialogue box and then hit Enter on the keyboard. Soil Properties are entered similarly, in a grid on the left of the Main Menu, in which each row represents a single soil layer or stratum.

Please also note that although the data-entry grids in the UA Slope 2.3 program may look similar to spreadsheets, the data cannot be cut, copied, or pasted like a spreadsheet. Figure 11 shows the Main Menu screen with the problem geometry and soil properties entered for the example problem.

Lastly, the user must define the Coordinates of the Crest of the slope and the Coordinates of the Toe of the slope. These coordinates have two purposes: first, to calculate the angle of steepness of the slope from horizontal ($\beta$); and second, to calculate the location of the drilled shafts on the slope ($\zeta$). The program does not allow slope angles steeper than sixty degrees, since the load transfer factor equation coded in the program is not calibrated for steeper slope angles. Furthermore, if the crest and toe coordinates are not defined, $\zeta$ cannot be determined, and $\eta$ will always evaluate as “0,” invalidating the results of the analysis. In the example problem,
the Coordinates of Crest are at the outside edge of the roadway embankment, and the Coordinates of Toe are at the toe of slope, where the failure surface exits. Please note that the drilled shafts must be placed between the Coordinates of Crest and the Coordinates of Toe, so ensure that these coordinates are to the left and right (respectively) of the part of the slope where drilled shafts might be installed.

Run the analysis first without the drilled shaft effect (Calculate without Drilled Shaft), so that the Factor of Safety for the existing condition may be appraised and correlated with the Factor of Safety from the computerized stability analysis (this should be 1.0). If the initial run of the UA Slope 2.3 program does not have a Factor of Safety of 1.0, adjust the soil properties or phreatic surface slightly until the Factor of Safety equals 1.0. Figure 12 shows the Main Menu screen with the Calculated Results of the analysis without the drilled shaft; the Factor of Safety of 1.00 is displayed at the upper left corner of the Main Menu.

To perform an analysis with the drilled shaft effect, the user must input the Drilled Shaft Information (geometry). Drilled Shaft Information consists of Diameter (D), center-to-center (CTC) Spacing (S), and X Coordinate (location). The X Coordinate is the offset of the centerline of the single row of drilled shafts from the Y-axis (the uphill boundary slice). For this reason, it is helpful to make the left (uphill) boundary at an even-numbered offset from the roadway centerline or baseline. If the failure scarp does not extend beyond the roadway centerline, the roadway centerline can be used as the boundary slice: this allows the X Coordinate of the drilled shafts to be the same as the roadway offset of the drilled shafts. If the failure scarp does extend beyond the roadway centerline, some other reference point must be used, and the difference between the boundary slice location and the roadway centerline must be subtracted from the X Coordinate of the drilled shafts to get the roadway offset of the drilled shafts.
For example, in the example problem, the landslide head scarp is at 1.8 feet left of the roadway centerline. Therefore, the left (uphill) boundary of the model in the UA Slope 2.3 program has been set at 10.0 feet left of the roadway centerline. If the drilled shafts were placed at X=50.0 feet in the model, they would be at an offset of 50.0 – 10.0 = 40.0 feet right of the roadway centerline.

Figure 13 shows the Main Menu screen with the Calculated Results of the analysis with the drilled shaft effect “Automatic Load Transfer Factor;” in the Drilled Shaft Information on the lower left of the Main Menu screen, the drilled shaft Diameter is 3.00 ft, the CTC Spacing is 9.00 ft, and the X Coordinate is 52.00 ft. Note that in the Chart, in the upper right corner of the Main Menu screen, the drilled shaft Diameter is 3.00 ft, the CTC Spacing is 9.00 ft, and the X Coordinate is 52.00 ft. Note that in the Chart, in the upper right corner of the Main Menu screen, the Factor of Safety of 1.30, the Force per Shaft of 169311.232 lb, and the Acting Point of the resultant, X: 52.00 ft and Y: 44.019 ft are displayed. The X coordinate of the Acting Point is always the same as the X Coordinate of the drilled shafts, while the Y coordinate of the Acting Point is two-thirds of the distance from the ground surface to the defined Slip Surface (the program represents the horizontal earth pressure load as a triangularly distributed load with an intensity of 0 at the ground surface).

Figure 13: UA Slope 2.3 Program results with Drilled Shaft

Drilled shafts should be analyzed for a variety of geometric configurations of diameter (D) and spacing-to-diameter ratio (S/D). For each combination of D and S/D, the drilled shafts should be analyzed at varying offset locations (X Coordinate). Tables and graphs should be made for each geometric configuration of the drilled shafts, showing the relationship between drilled shaft location (X Coordinate) and Factor of Safety, and between drilled shaft location (X Coordinate)
and Force per Shaft. If the drilled shaft X Coordinate is not the same as offset from roadway centerline (if the Y-Axis in the UA Slope 2.3 program is not at roadway centerline), then the drilled shaft location should be adjusted to roadway offset in the graphs. Figure 14 shows an example of the Factor of Safety versus Offset graph for the example problem.

![Factor of Safety vs. Shaft Offset from Roadway Centerline](image)

**Figure 14: Factor of Safety vs. Shaft Offset from Roadway Centerline**

Note that in the example graph, the X-axis represents offset from roadway centerline, which in this case, is 10 feet less than drilled shaft location (X Coordinate) used in the UA Slope 2.3 program. Also, the diameter of the shafts is provided in inches, and shaft geometry is expressed as a spacing-to-diameter ratio (S/D). It can be seen that the Factor of Safety generally increases from 1.0 to a maximum somewhere near the middle of the failure, and then decreases back to 1.0 at the toe of the failure. Note also that the Factor of Safety decreases as the spacing between shafts increases, and as shaft size increases – as a larger shaft size at the same S/D ratio has a larger space between shafts.

The UA Slope 2.3 program has a built-in feature to speed up the graphing process. The program includes a template input spreadsheet, titled “UASlope_Default.xlsx,” into which the problem geometry can be input per Section 4.4 of the UA Slope 2.3 Program User’s Manual. A separate template spreadsheet will have to be created for each combination of D and S/D; however, the spreadsheet can be set up to iterate through a range of X Coordinates at a defined interval. This greatly reduces the number of times the program will have to be run for a full analysis. A new copy of the spreadsheet is saved on the executing computer at the file path “C:\spile\Excel_Results,” which will contain a tabular set of results along with a pair of graphs for Factor of Safety versus Offset and Shaft Load versus Offset. It should be noted that the graduate student who programmed this behavior did not understand the difference between X Coordinate and Offset from Roadway Centerline, therefore the first line in the table (with the minimum X
Coordinate) will always be Offset 0 in the excel output file. The offset will have to be manually corrected by the engineer performing the analysis.

Figure 15 shows the associated Shaft Load versus Offset graph for the example problem. It can be seen from this graph that the shaft load tends to follow a similar trend to the Factor of Safety, increasing from 0 to a maximum somewhere near the middle of the failure, and then decreasing back to 0 at the toe of the failure; this behavior is typical.

![Figure 15: Shaft Load vs. Shaft Offset from Roadway Centerline](image)

Based on the two sets of plots, a shaft size, geometry, and offset should be chosen which will maximize Factor of Safety, minimize shaft load, and conform to other constraints, such as right-of-way restrictions, and other issues which might affect constructability, such as slope steepness and waterways. The minimum Factor of Safety for slope stability required by ODOT is 1.3, therefore, an offset and geometry are typically chosen to meet this minimum Factor of Safety, and then the drilled shafts are assessed structurally, to determine if they are capable of resisting the predicted shaft load. In the example problem, drilled shafts of 36-inch diameter, with S/D=3 (9-foot center-to-center spacing) at an offset of 42 feet from roadway centerline (X Coordinate of 52 feet) had a Factor of Safety of 1.30, and were selected for design (see Figure 13 for the actual results of this analysis).

In some instances, it may be impossible to achieve the minimum Factor of Safety with a row of spaced drilled shafts, or right-of-way or constructability restrictions may mean that a sufficient offset to achieve the minimum Factor of Safety cannot be utilized. In this case, a drilled shaft wall may be necessary. This could take the form of a drilled shaft soldier pile and lagging wall, a “plug-pile” lagging wall, a tangent drilled shaft wall, or a secant drilled shaft wall.
Soldier pile walls consist of a row of drilled shafts spaced at typically a 4-foot to 8-foot center-to-center spacing. HP-section or W-section steel beam reinforcements (soldier piles) are inserted vertically into the shafts, with the webs of the steel sections placed parallel to the direction of the landslide movement. Structural concrete is poured into the shafts up to the bottom of the proposed depth of lagging. Low-strength grout is often poured on top of the structural concrete to finish filling the holes. The soil and grout are then excavated down to the top of the structural concrete, and then treated timber or precast concrete lagging panels are inserted in-between the steel beams, held in place by the flanges of the beams.

A plug-pile lagging wall consists of a row of structural drilled shafts spaced at a two-shaft-diameter center-to-center spacing (S/D=2). These structural shafts are reinforced with steel cages or steel beam sections, and then filled for their full length with structural concrete. Plug-piles of the same diameter are then drilled in-between the structural shafts, tangent to the structural shafts. The plug-piles are typically shallower (they usually do not penetrate bedrock), and serve the purpose of lagging, however, they are not connected to the structural shafts. The plug piles are filled with structural concrete but are not steel reinforced.

A tangent drilled shaft wall is similar to a plug-pile wall except that all of the drilled shafts are structural, steel-reinforced shafts. A row of structural shafts is drilled at two shaft diameter center-to-center spacing (S/D=2), reinforced, and back-filled with structural concrete. Additional structural shafts are then drilled in-between the existing structural shafts, tangent to the existing shafts. These in-between shafts are drilled to the same depth as the first set of shafts, reinforced the same, and also back-filled with structural concrete.

A secant drilled shaft wall is similar to a tangent drilled shaft wall, except that the spacing between drilled shafts is less than the diameter of the drilled shafts. First, a row of “secondary shafts,” or unreinforced shafts, are drilled at slightly less than a two shaft diameter center-to-center spacing (S/D<2). 60 Inches center-to-center spacing is a typical spacing for 36-inch diameter secondary shafts, leaving 24 inches of space between shafts. The secondary shafts are then filled with concrete, and primary or “king” shafts are drilled between the secondary shafts, overlapping the secondary shafts by several inches. The primary shafts are steel reinforced and filled with structural concrete. The secondary shafts can be filled with structural concrete, but are sometimes filled with lean concrete in order to make the drilling for the primary shafts easier. Secant drilled shaft walls are used as retaining walls where a water-tight wall is required, but are not common for landslide stabilization, as they are difficult to construct, and do not necessarily have the same structural capacity as a tangent drilled shaft wall.

If the lateral earth loads are so high that a wall cannot be built to stand in a cantilever condition, any of the above wall types can be reinforced with grouted ground anchors (tiebacks) or with deadman anchors.

The UA Slope 2.3 program may also be used to calculate the loading on a drilled shaft retaining wall. For this case, set the drilled shaft Diameter (D) and the CTC Spacing (S) between shafts as presented above. However, in this case, the Manually Defined Load Transfer Factor setting under Drilled Shaft Information should be used. This setting allows the Load Transfer Factor (η) to be explicitly defined; in the case of a wall, η should be set to zero (0), meaning that the drilled shafts take up the full load from the uphill soil slice, and no load is passed through to the downhill soil slice. The Factor of Safety calculated by the UA Slope 2.3 program should be ignored in
the case of analysis for a wall. This Factor of Safety is for the *entire* defined shear failure surface, not for the drilled shaft retaining structure. If we use a wall, we often assume that the slope below the wall will continue to fail, and that the Factor of Safety for the slope will continue to be marginal or inadequate. Factor of Safety for the wall is assessed through a structural analysis, and is separate from the Factor of Safety for stability of the slope.

Note that in some cases, generally where the slope is fairly flat, and there is a large amount of the failure surface downhill of the drilled shaft retaining structure which may offer resistance to movement, the UA Slope 2.3 program may not be able to successfully calculate a factor of safety. This is because the downhill soil mass, in combination with the drilled shaft retaining structure, offers so much more resistance than the magnitude of the load on the back of the structure, that the factor of safety of the system exceeds a program limit of 100. In this event, the program will output a factor of safety of “100;” the load on the back of the drilled shaft retaining structure may still be conservatively utilized in further structural analysis, but it will be impossible to estimate the factor of safety of the entire system in the existing configuration.

**E. LPILE Analysis**

Once the load on the shafts is determined, we need to determine the reaction of the shaft to the load, including the drilled shaft head displacement, the shear and moment distributions, and determine whether the drilled shaft is structurally capable of resisting the load. Any capable p-y analysis software, such as LPILE, or FBPIER may be used. ODOT OGE currently uses the program LPILE Version 2018.10.05, developed by Ensoft, Inc., therefore, the examples in this section will refer to this version of LPILE.

**1. Conversion of Force per Shaft to Distributed Lateral Loading**

The UA Slope 2.3 program calculates an unfactored horizontal earth pressure (EH) resultant load per shaft, however, for proper structural analysis of drilled shaft reaction, we need to convert this to a more realistic distributed load. We note that the actual load distribution is complex, and impossible to determine without direct measurement or back-calculation through measurement of displacements, however, we feel that a triangular load distribution is a close enough approximation of the actual condition to develop a realistic calculation of distributed shear, moment, and displacement in the drilled shaft.

The depth to the shear surface, depth to bedrock, and single shaft resultant force need to be determined at the chosen offset for the placement of the drilled shafts, based on the desired Factor of Safety predicted by the UA Slope 2.3 program. Utilizing these known factors, we can calculate a triangular distribution of loading, from zero (0) at the ground surface to a maximum at the depth of the shear surface. This load is represented solely as a horizontal distributed load, with no vertical component, as this is a more conservative assumption, providing the maximum lateral loading. Research has shown that the vertical load component is either insignificant, or tends to provide a small amount of compression to the shaft, which marginally increases bending resistance. If using LPILE, the distributed load must be converted into units of pounds per inch (lb/in) of length along the drilled shaft.

Do not represent the load on the shaft as a single resultant point load, and “cut off” the top of the shaft at the point of application of this resultant load. This method does not realistically
predict either the shape or magnitude of shear and moment distributions, and cannot predict the displacement at the drilled shaft head.

2. p-y Modification Factors for Group Action

If the drilled shafts are at a center-to-center spacing closer than about 3½ diameters, a reduction in the soil resistance $p$, for the p-y curve behavior of the soil, must be considered. The loss in capacity is due to soil-structure-soil interaction, and an overlap in the region of the soil that provides passive resistance to the deflection of the drilled shafts when placed in a closely-spaced group. This effect does not occur where drilled shafts are embedded in a relatively much stiffer material, such as bedrock or concrete, where the stress field effects are very limited, and the material does not deform substantially under the design loadings. Therefore, in LPILE, apply the p-multiplier ($P_m$) from the ground surface (or artificially lowered ground surface) to the top of bedrock or to the bottom of the drilled shaft, whichever is shallower.

Reese, Isenhower, and Wang, “Analysis and Design of Shallow and Deep Foundations” (2006) publish an equation for the pile group p-reduction factor for a single row of piles placed side by side, $P_m=0.64(S/D)^{0.34}$, for $1\leq S/D<3.75$, where $0.5\leq P_m\leq1.0$. This is an empirical relationship based on testing by a number of researchers in a number of different soil types. Utilize this equation for determination of the p-multiplier.

3. Soil Layering and p-y Models

LPILE will calculate a passive resistance, “Mobilized Soil Reaction,” for the soil mass in reaction to the lateral load imposed on the shaft. The actual passive resistance of the downhill soil mass in a landslide will be reduced due to translation of the soil mass away from the drilled shafts; however it will not usually become zero, as “full depth crack” theories assert. In order to model the loss of passive resistance of the downhill soil mass, we recommend three separate methods, depending on the type of drilled shaft retaining structure installation.

For the case of a row of spaced drilled shafts, in which the downhill soil mass must remain in place, and where soil arching and downhill load transfer are dependant mechanisms for retention of the uphill soil mass, use a load transfer reduction, based on the Factor of Safety (FS) of the existing slide plane, calculated by the UA Slope 2.3 program with the inclusion of the drilled shafts. Please note, that for this design case, the UA Slope FS must meet the minimum required Factor of Safety for an unreinforced slope (FS ≥ 1.30), and the slope must have a steepness of 2H:1V or flatter, per GB2. In this case, the p-multiplier, as determined under “2. Modification Factors for p-y Curves” is reduced above the shear plane. The reduced p-multiplier is equal to $[(1-1/FS) \times P_m]$, or $[P_m - (P_m/FS)]$. For example, if S/D = 3.0 and FS = 1.30, then $P_m = 0.930$, and the p-multiplier above the shear plane = $[0.930 - (0.930/1.30)] = 0.215$.

For the case of a retaining wall in which the downhill soil mass will be left as-is, and if stability analysis downhill of the proposed wall shows that the downhill soil mass does not meet the minimum required Factor of Safety for an unreinforced slope (FS ≥ 1.30), consider the downhill soil mass to be unstable. In this case, we may assume that the downhill soil mass will continue to fail away from the wall, while the wall retains the uphill soil mass. In order to model the anticipated loss of passive resistance of the downhill soil mass, artificially lower
the ground surface in the LPILE analysis, completely discounting the passive resistance of the soil between the existing ground surface and the artificially lower ground surface. To do this, first determine the angle of steepness of the slope from horizontal, downhill of the drilled shafts ($\beta_{dh}$); then determine the depth to the shear surface at the location of the drilled shafts ($d_t$). For slopes of steepness from $\beta_{dh}=0^\circ$ to $45^\circ$, lower the ground surface by an amount equal to $d_t\tan(\beta_{dh})$. For slopes of steepness $\beta_{dh}=45^\circ$ or more, discount the entire soil mass from the actual ground surface to the depth of the shear failure surface. Model all soil layers below the artificially lower ground surface normally, per the LPILE user’s manual.

For the case of a retaining wall in which the downhill soil mass will be regraded to a stable slope (lower at the base of the wall than behind the wall), set the ground surface in LPILE equal to the proposed regraded ground surface and model all soil layers below the proposed ground surface as in the proposed condition.

4. Drilled Shaft Length
Embed the drilled shaft in a solid stratum below the shear failure such that deflection at the drilled shaft head will be constrained to appropriate serviceability limits (see Section 8, below, for details of the required serviceability limits). Ideally, embed the shaft into bedrock to provide resistance to deflection. Regardless, extend the drilled shaft a minimum of 10 feet below the shear surface. Also select the total drilled shaft length such that the drilled shaft is geotechnically stable (see Section 9, below).

5. Steel Reinforcement
In the past, it has been common to reinforce concrete drilled shafts with steel reinforcing bar (re-bar) cages. However, due to the expense in time and money for labor to construct re-bar cages, and the relative fragility of these cages before they are embedded in the concrete shaft, it has recently been the practice to more commonly utilize steel HP-section or W-section beams as reinforcement. These steel sections are generally cheaper per pound of steel than re-bar cages, often require less weight of steel per length of drilled shaft, require no cost in labor for fabrication, and can be easily and quickly installed with little danger of distorting or otherwise damaging them during or before installation. However, we leave it up to the designer to choose whether to use a concrete shaft reinforced with steel re-bars or with a steel beam section. Alternately, the designer may design for both options, so that the contractor may choose which method to employ. Sometimes, we will want both options to be used simultaneously – for example, some historical projects have used primarily steel beam reinforcement, but used re-bar reinforcement for selective shafts in which research instrumentation was installed.

Although the steel beam section is actually embedded in a concrete shaft, analyze the shaft structurally as a steel pile without concrete. We acknowledge that this is conservative, as it is generally recognized that concrete encased sections are restrained from both local and lateral buckling, and that the concrete stiffens the web and allows an increased shear resistance due to tension field effects. However, at present there is little research into the shear resistance of concrete encased steel sections. The AISC code addresses concrete encased steel sections and specifies that the shear resistance be based on the steel section alone. In the case of steel beam section reinforced drilled shafts, the concrete exists primarily to transfer load to the steel member, and we are relying on the steel for shear and moment resistance. Although this produces a conservative design, we recommend this approach...
until more research is available into the behavior of composite sections. In the case of drilled shafts with steel sections used as soldier piles, we do not feel this approach is conservative, as a significant portion of the steel sections is exposed above the concrete to support the lagging.

6. **Section Type, Dimensions, and Cross-section Properties**

   When analyzing a steel beam section reinforced drilled shaft, select “Elastic Section (Non-yielding)” under the Section Type in LPILE. Select the Structural Shape “Circular without Void” under Dimensions and Properties. In order to develop the proper reaction from the soil in LPILE, set the Elastic Section Diameter equal to the nominal borehole diameter for the drilled shaft. However, set the Moment of Inertia and Area under Elastic Section Properties equal to the actual values of Iₓ and Aₛ for the embedded steel HP or W beam section. Set the Modulus of Elasticity equal to that for a steel section alone (approximately 29,000,000 psi), not for a composite section.

   The ground surface should be represented as level, not inclined. Inclination of the ground surface is usually used in LPILE to represent pile batter, and in any event, represents a reduction in the soil resistance near the ground surface, which is not relevant, as we are already discounting soil resistance near the ground surface.

   When analyzing a steel re-bar reinforced concrete shaft, select “Round Concrete Shaft (Bored Pile)” under Section Type in LPILE. Set the Section Diameter under Shaft Dimensions equal to the nominal borehole diameter for the drilled shaft. Under Rebars, select the appropriate options to define the proposed steel re-bar arrangement. Set the Yield Stress and Elastic Modulus equal to the values for the type of longitudinal steel reinforcing bars to be used. Under Concrete, set the Compressive Strength equal to that for the structural concrete of the shaft (typically 4000 psi compressive strength). While 4500 psi compressive strength concrete is typically specified, 4000 psi compressive strength is assumed for design, due to quality control limitations on drilled shaft concrete placement. If a concrete compressive strength greater than 4500 psi is to be specified, assume 0.9 f′c for the design.

   Unless there is a constructability concern which dictates a smaller rock socket diameter, set the diameter of the drilled shaft the same over its entire length. Use ASTM A709 minimum 50 ksi yield strength steel for the structural steel used in a steel reinforcing beam section. Use 60 ksi yield strength epoxy-coated steel for re-bar reinforcement, per C&MS Item 524. Typically, use Class QC 5 concrete, per C&MS Item 524. If using a drilled shaft reinforced with a steel beam section, see the Plan Note “DRILLED SHAFTS FOR SLOPE STABILIZATION;” found in Appendix 1, attached to the end of this Geotechnical Bulletin. If the drilled shafts are of 7 feet or greater in nominal diameter, use QC 4 Mass Concrete instead.

   If analyzing a steel re-bar reinforced concrete shaft, the “Round Concrete Shaft (Bored Pile)” Section Type will result in a non-elastic, yielding analysis (corresponding to LPILE Analysis Type 3, “Computations of Ultimate Bending Moment and Pile Response Using Nonlinear EI,” in previous versions of LPILE) which takes into account the cracking of the concrete section with deflection, and the resulting loss in stiffness. If analyzing a steel beam section reinforced drilled shaft, the Elastic Section (Non-yielding) Section Type will result in an elastic analysis.
(corresponding to LPILE Analysis Type 4, “Computations of Ultimate Bending Moment and Pile Response with User-Specified EI,” in previous versions of LPILE) which uses a constant beam stiffness, which is unaffected by deflection of the beam.

7. Pile-Head Loadings and Options
At the ground surface, the drilled shaft should be free to move both laterally and rotationally. In LPILE, there are multiple Pile-Head Loading Type options to define boundary conditions and loading at the drilled shaft head. The option “1 Shear [F] & 2 Moment [F-L]” should be selected, with a value of zero (0) input for both the shear and moment loading. This defines a drilled shaft which is free at the head, with a moment and shear which will decrease to zero at the drilled shaft head. All other options define rotational or displacement fixity of the drilled shaft head or define a deformation at the drilled shaft head.

Set the option “Compute Top Y vs. L?” to “Yes,” as this will aid in determining the required length of the drilled shaft to resist the lateral loading (see Sections 8 and 9.a below).

Represent horizontal earth pressure (EH) loading on the drilled shaft as a triangular distributed load – as noted previously – with a value of zero at the ground surface (drilled shaft head), and a maximum at the depth of the shear surface. If the horizontal distance between the drilled shafts and traffic loading is less than or equal to half the depth to the shear surface at the location of the drilled shafts ($d_t$), also apply an (unfactored) vehicular live load surcharge (LS) to the drilled shafts equal to two feet of soil with a unit weight $\gamma_s = 125$ pcf, per AASHTO LRFD Bridge Design Specifications, Article 3.11.6.4.

Run LPILE twice for each loading case; running analyses with unfactored loading for the Service I Limit State, to determine drilled shaft head deflection; and with factored loading for the Strength I Limit State, to determine the structural shear and moment capacity of the drilled shaft. For the factored Strength Limit State condition, use a load factor of $\gamma_{LS} = 1.75$ for the vehicular live load surcharge (LS) and a load factor of $\gamma_{EH} = 1.50$ for the horizontal earth pressure (EH), per AASHTO LRFD Bridge Design Specifications, Article 3.4.1.

8. LPILE Output
After the computational analysis of the drilled shaft behavior is completed, there are several items which should be inspected immediately. LPILE can produce a plot of “Top Deflection versus Length” (see Section 7, above). For both the unfactored Service Limit State analysis and the factored Strength Limit State analysis, the length(s) at which either of these plots climbs to infinity or becomes indeterminate is the point at which the drilled shaft length becomes too short, and a length will have to be chosen beyond this point. If it appears that several iterations may be required to determine the optimal drilled shaft length through incremental increases, it may be more efficient to analyze a drilled shaft which is known to be too long, and then cut down the drilled shaft length to the optimal point. Regardless of the results of the deflection plots, embed the drilled shaft a minimum of 10 feet below the shear surface.

LPILE also generates a plot of Lateral Deflection versus Depth and calculates a (maximum) “Pile-head deflection.” For the unfactored Service Limit State analysis, limit the maximum Pile-head deflection to 1% or less of the drilled shaft length above bedrock (if not embedded in bedrock, this is 1% of the total drilled shaft length); however, if the drilled shafts are to be
installed within 10 feet of the edge of pavement, limit the Pile-head deflection to 2” or less. Use whichever serviceability limit requires the least deflection. If the drilled shaft deflects more than the required serviceability limit, we consider this to represent failure, and a stiffer reinforcement or larger diameter drilled shaft will have to be selected and re-analyzed.

LPILE also provides maximum values for shear and moment in the shaft. Use these values, from the factored Strength Limit State analysis, in the structural analysis of the shaft, in order to determine if it is structurally capable of resisting the loading without failing in either bending or shear.

9. Geotechnical Resistance
Also perform a check of geotechnical resistance against overturning of the drilled shaft. The check of geotechnical resistance is not a consideration of the structural capacity of the drilled shaft, but of the geotechnical resistance of the soil and bedrock to resist excessive overturning movement of the drilled shaft. Two options are available for performing this check:

   a. LPILE Deflection Analysis
This is by far the simpler method to check geotechnical resistance. Consider the “Pile-head deflection” calculated by LPILE from the factored Strength Limit State analysis. If the deflection does not indicate failure – either failure of the program to converge at a solution, an infinite deflection, or a very large deflection (typically around 100 inches) – then we consider the drilled shaft to be stable, with adequate geotechnical resistance against overturning. It is acceptable for the Strength Limit State analysis deflection to be quite large, so long as the Service Limit State analysis deflection meets the required serviceability limits (see Section 8, above). The LPILE plot of Top Deflection versus Length can be helpful to find the point of optimized drilled shaft length.

   b. Moment Equilibrium Analysis
Demonstrate moment equilibrium about the toe of the drilled shaft, per AASHTO LRFD Articles 3.11.5.6, 11.6.3.5, and 11.8.4.1, with reference to AASHTO LRFD Figures 3.11.5.6-1 through 3.11.5.6-3, and utilize the methodology as outlined in AASHTO LRFD Commentary C11.8.4.1. Please note that Figures 3.11.5.6-1 through 3.11.5.6-3 do not include the effects of vehicular live load surcharge (LS), which will have to be added by the engineer. Also note that the figures do not utilize load or resistance factors (all loads shown are nominal); apply appropriate load and resistance factors as described by AASHTO LRFD Commentary C11.8.4.1.

If the drilled shaft exhibits excessive deflection or cannot achieve moment equilibrium at the analyzed length, we consider this as failure. In this case, deeper embedment of the drilled shaft or a larger diameter drilled shaft may be required to meet the requirements of geotechnical resistance against overturning.

Do not utilize the Geotechnical Strength Limit State check per FHWA GEOTECHNICAL ENGINEERING CIRCULAR NO. 10, PUBLICATION FHWA-NHI-10-016, DRILLED SHAFTS: CONSTRUCTION PROCEDURES AND LRFD DESIGN METHODS (GEC 10), Section 12.3.3.3.1. This check is not intended for retaining structures, and will produce overly conservative results.
F. STEEL BEAM SECTION DESIGN

After determining the Service Limit State lateral deflection of the shaft and the Strength Limit State moment and shear distributions for the single shaft load by analysis with an appropriate p-y analysis software, such as LPILE, or FBPIER, check that the shaft reinforcement is capable of resisting the calculated factored maximum moment and maximum shear force. This section is provided to give guidance for the design of steel beam W-sections or HP-sections as drilled shaft reinforcement, as this is not typical practice at this time. If designing a conventional re-bar reinforced concrete shaft, utilize the LRFD design procedures for laterally loaded drilled shafts, per FHWA GEC 10, Chapter 12 and Chapter 16.

ODOT is now utilizing Load and Resistance Factor Design (LRFD) methods, per AASHTO LRFD Bridge Design Specifications, for the design of steel beam sections resisting shear and moment due to lateral earth loadings. Per FHWA Policy Memorandum Related to Structures, dated June 28, 2000, Load and Resistance Factor Design (LRFD) Specifications are required for all new culverts, retaining walls, and other standard structures on which States initiate preliminary engineering after October 1, 2010. It is no longer acceptable to use Load Factor Design (LFD) methods or Allowable Stress Design (ASD) methods.

Use steel with a minimum yield stress (F_y) of 50 ksi (ASTM A709 grade 50) for beam sections used for landslide stabilization drilled shaft reinforcement. Per ODOT Bridge Design Manual (BDM) Section 302.4.1.1.C, ASTM A709 grade 36 is not recommended and is being discontinued by the steel mills.

1. Minimum Concrete Cover for Reinforcing Steel

Whether designing a drilled shaft reinforced with a steel reinforcing bar (re-bar) cage or with steel HP-section or W-section beams, ensure that the reinforcement can fit within the drilled shaft with the minimum required concrete cover per BDM 301.5.7 and C&MS 509.04.B. The minimum concrete cover between soil and steel reinforcement for a drilled shaft of 4 feet or less in diameter is 3 inches. The minimum concrete cover between soil and steel reinforcement for a drilled shaft greater than 4 feet in diameter is 6 inches.

2. Load and Resistance Factor Design (LRFD)

For Strength Limit State design, use a load factor of γ_{LS}=1.75 for the vehicular live load surcharge (LS) and a load factor of γ_{EH}=1.50 for the horizontal earth pressure (EH), per AASHTO LRFD Bridge Design Specifications, Article 3.4.1. Use factored loading and resistance for structural capacity (flexure and shear) design of the steel beam section reinforcement. Use a resistance factor φ_f=1.00 for flexural resistance and a resistance factor φ_v=1.00 for shear resistance per AASHTO Article 6.5.4.2. Check the flexure resistance of the steel beam section according to AASHTO Article 6.10.8. Check the shear resistance of the steel beam section according to AASHTO Article 6.10.9. If the steel section is embedded in a concrete drilled shaft, assume that it has continuous lateral bracing and transverse stiffening. If the steel section extends above the drilled shaft and is unbraced (as in a soldier pile wall) analyze the steel section for flexural buckling with an unbraced length equal to the exposed length, per AASHTO Article 6.9.4.1.2.

3. Iterative Design Process
Use an assumed steel section for LPILE (or other comparable software) analysis to
determine the drilled shaft head deflection (Service Limit State) and distributed and maximum
moment and shear (Strength Limit State) for the beam. Check that the selected steel section
is capable of resisting the calculated maximum moment and maximum shear per AASHTO
LRFD procedures, and check that the drilled shaft head deflection is less than the required
serviceability limit (see Section E.8 above). If these requirements are not met, select a more
capable steel section. If the minimum capable steel section will not fit within the selected
nominal drilled shaft diameter with the minimum required concrete cover, consider a larger
diameter drilled shaft. If the deflection, flexure, and shear requirements are greatly exceeded,
consider selecting a lighter steel section (and possibly smaller diameter drilled shaft) to save
cost.

Every time a new steel section or a new nominal shaft diameter are selected, recalculate the
drilled shaft reaction with LPILE, and check the deflection and the flexure and shear
resistance of the steel section per AASHTO LRFD specifications.

G. SLOPE PROTECTION AND REGRADING

Once a structural solution has been designed to remediate the slope failure or retain the soil
mass, either with a row of spaced drilled shafts or with a wall, ensure that critical parts of the
remainder of the slope geometry will remain in place, so that the structural solution will not fail.
Failure of the structural solution does not necessarily mean failure of the structural elements.
Failure also includes any movement of the soil mass, independent of the structural fix, which
compromises the integrity of the facility the drilled shafts are designed
to protect.

If using a row of spaced drilled shafts, per the Liang method, and if the slope below the shafts
continues to move, or if a new instability develops below the shafts, this system is jeopardized.
This solution depends on soil arching and a percentage of the load being transferred between
the shafts, through to the downhill soil mass. This mechanism increases the Factor of Safety
(the nominal resistance versus load) of the entire landslide by effectively decreasing the method
of slices interslice force. However, it depends on the soil mass downhill of the shafts to support
the remaining interslice force. If the soil mass downhill of the shafts is removed, the passive
support of this soil is eliminated, and the soil mass uphill of the shafts will fail between the shafts,
causing the entire system to fail. In this case, the drilled shafts could remain in place without
suffering a structural failure.

However, if the structural solution is designed to depend on the passive resistance of the
downhill soil mass below the shear failure surface to provide support for the structural elements,
and that soil mass fails away – either through a new shear failure or by erosion – the structural
elements of the system may fail. Furthermore, if a new shear failure develops uphill of the
structural retention system, we regard this as failure of the system, even though no failure of the
structure occurs.

Therefore, it is important to protect the integrity of the remainder of the slope once a structural
solution has been selected and designed. Perform slope stability analyses of the slope both
uphill and downhill of the structure. If the soil mass uphill of the structure is found to have
inadequate stability, the uphill slope may need to be regraded, may need reconstruction with
special benched excavation and embankment backfill (see GB2), may require the addition of
subsurface drainage, or the structure may need to be modified (either moved to a new lateral location or increased in height) to properly retain the uphill soil mass. If using unreinforced embankment fill material or natural soil per C&MS Item 203, the uphill slope may not be regraded to steeper than 2H:1V. If using a Reinforced Soil Slope (RSS), the uphill slope may be steeper than 2H:1V, but no steeper than 1H:1V. However, analysis of RSS stability is beyond the scope of this document.

If the slope downhill of the structure is found to have inadequate stability, other measures may have to be taken, depending on the type of structural solution. If using a row of spaced drilled shafts, the downhill slope must be stabilized by one of the methods recommended above, or the row of shafts must be moved further downhill, in order to increase the stability of the lower slope. If the shafts are moved, the shaft loading will change, and the entire system will need to be redesigned. Regrading or reconstructing the lower slope may not be practical, due to limiting geometry at the toe of the slope. If neither movement of the shafts nor regrading of the lower slope can successfully increase the stability, a wall will be necessary.

If a wall is used, failure of the downhill soil mass may not contribute to failure of the system overall, as long as the material into which the drilled shafts are embedded (usually bedrock) does not fail, and as long as the drilled shafts are capable of standing cantilever or are reinforced by tiebacks. If there is a chance that the material into which the drilled shafts are embedded may fail along with the downhill portion of the landslide, design the drilled shafts for this condition, and increase the embedment.

Regardless of structural stability of the drilled shaft reinforcing system, there may be other reasons: environmental, aesthetic, or otherwise, for which the downhill soil mass may need to be stabilized. In this case, the downhill slope may need to be flattened, and/or the soil may need to be cut to below the existing shear failure surface. If the slope failure is along the bank of a river or other stream, erosion control – typically C&MS Item 601 Rock Channel Protection (RCP) – may be necessary at the base of the slope in order to protect against erosion undercutting the toe of the slope and inducing an additional instability. Also, if along a body of water which is prone to flooding, design the system to resist loadings under the “normal” condition, the 100-year recurrence flood condition, and the rapid-drawdown condition. In general, design the structural system for the worst-case conditions which may be anticipated during the life of the structure.
Appendix 1: Plan Note “DRILLED SHAFTS FOR SLOPE STABILIZATION”
Designer Note: This note is for slope stabilization structures that are buried, i.e. they do not have any lagging above ground. The note assumes that the drilled shafts are designed to rely only on the structural steel member and that the concrete in the drilled shaft is only to fill the void and is not structurally significant.

DRILLED SHAFTS FOR SLOPE STABILIZATION

Item 524, Drilled Shafts, __" Diameter, Above Bedrock, As Per Plan
Item 524, Drilled Shafts, __" Diameter, Into Bedrock, As Per Plan

This work consists of furnishing and installing drilled shafts for slope stabilization structures. The drilled shafts are reinforced with structural steel members instead of reinforcing steel cages. Furnish and install the drilled shafts in accordance with CMS 524 except as modified and supplemented below.

Excavate the hole for the drilled shaft within 3 inches of the plan location. The design is based on a maximum depth from ground surface to bedrock of __ feet. If field conditions indicate greater depths, notify the Engineer for further evaluation.

Furnish structural steel members according to the plan requirements and conforming to ASTM A572, Grade 50. Do not field weld or splice structural steel members. Place the steel member within the hole so it is vertical and not inclined more than 1 inch between top to bottom. Center the steel member within the hole. Place the steel member so that the flanges are parallel to the centerline of the row of drilled shafts. Do not allow the orientation of the flanges to vary by more than 10 degrees. Support the steel member so that it does not move during concrete placement.

Use Class QC 5 concrete according to CMS 511. The Contractor may place concrete using the free fall method provided the depth of water is less than 6 inches and the concrete falls without striking the sides of the hole. Pouring concrete along the web of the structural steel member is acceptable.

Check the position, the vertical alignment and orientation of the structural steel member immediately after concrete placement. Make corrections as necessary to meet the above tolerances.

Method of Measurement: The Department will measure Drilled Shafts Above Bedrock, As Per Plan, along the axis of the drilled shaft from the existing ground surface to the top of bedrock, as determined by the Engineer. The Department will measure Drilled Shafts Into Bedrock, As Per Plan, along the axis of the drilled shaft from the top of bedrock to the bottom of the drilled shaft, as determined by the Engineer.
Appendix 2:
UA Slope 2.3 Program User’s Manual
A User’s Manual

for

UA Slope Program

Version 2.3

December 2015
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1. INTRODUCTION

The computer program UASLOPE 2.3 is a modified version of a previous computer program UA Slope 2.1 developed by Liang (2010) for analyzing a slope with or without a single row of spaced drilled shafts and/or anchors to determine the geotechnical factor of safety and the net force on each drilled shaft. A probabilistic version of UA Slope program (i.e. UASLOPE3.0) developed by Liang and Li (2013) has been released recently to account for the uncertainties of soils and drilled shafts. UASLOPE 2.3 is a deterministic version of UA Slope program, in which the basis of the theory and the validation were presented in the main text of the project report by Liang (2015). Even though the interface of the UASLOPE 2.3 program is user-friendly and quite straightforward, it was deemed appropriate to create a user’s manual to provide instructions on how to use the input interface for generating an appropriate input model for computer runs. Computations of the involved theories were fully coded into the computer program; therefore, no calculation tasks need to be performed by the program users. Nevertheless, it is important to note that the users should possess fundamental knowledge of soil mechanics, foundation engineering, and slope stability analysis methods in order to successfully implement the program. More importantly, it is highly recommended that users consult the main text of this report to get a detailed understanding of the theories and equations used in developing this computer program, paying particular attention to the limitations and range of applicability of the program. The computer analysis results should be interpreted by experienced engineers to ascertain the reasonableness of the computational results. In general, this manual provides background information on the UASLOPE program. An illustrative example is used to help explain how the input data should be prepared for subsequent computer runs.
2. BACKGROUND

UASLOPE 2.3 is a modified version of the previous program UASLOPE 2.1 that incorporates new equations to account for the arching effects in an anchor–shaft/slope system. A new user interface was developed in UASLOPE 2.3 to enable quick and easy input of the parameters needed in the analysis. Extensive beta testing of the coded program was carried out by comparing UASLOPE 2.3 results with other commercially available software, such as GSLOPE and STABL Windows version, for slope stability computation of slopes without drilled shafts. As to the validation of the applicability of UASLOPE 2.3 for analyzing the factor of safety and net force on the drilled shaft of an anchor–shaft/slope system, excellent comparisons between UASLOPE 2.3 predictions and 3-D finite element simulations using strength reduction techniques for about 90 cases were documented in the main report (Liang, 2015). Thus, within the range of slope geometry, shaft dimension and spacing, anchor force and angle, and soil strength parameters, the UASLOPE 2.3 program can be used with confidence for designing an optimized anchor–shaft/slope system that has an adequate geotechnical factor of safety for the system and the lowest construction cost. Structural design of the drilled shaft can be accomplished once the net force on the shaft is computed by UASLOPE 2.3. The net force computed by the UASLOPE 2.3 program is the net force on the portion of the drilled shaft above the failure surface. Therefore, this force needs to be assumed as a triangularly distributed load in the portion of drilled shaft above the failure surface in the LPILE analysis. Meanwhile, the horizontal component of the anchor force will be applied at the top of the drilled shaft as a shear loading condition in the LPILE analysis for the anchor–shaft/slope system. An appropriate load factor based on the current AASHTO LRFD Bridge Design Specifications should be applied to obtain the factored load combinations for structural design of drilled shafts. However, the unfactored load combinations should be used to compute the shaft deflection for checking the serviceability of the structures under the working load conditions.
3. LIMITATIONS

The theoretical basis of the UASLOPE 2.3 program in computing geotechnical factor of safety of an anchor–drilled shaft/slope system is the recognition of the reduced driving forces in the slope due to the anchor force and load transfer from the soil to the drilled shaft through arching mechanisms. Therefore, the essential requirement for this theory to work is that arching would indeed develop in the field application and that this arching effect would be permanent. Some of the conditions that may prohibit the development of an arching condition in an anchor–shaft/slope system include, but are not limited to, the following:

(a) A liquefiable sand layer that has a tendency to flow around the drilled shaft structures after liquefaction;

(b) A very soft soil layer that may squeeze through spaces between the drilled shafts;

(c) Narrowly spaced or widely spaced drilled shafts where arching could not develop;

(d) Stiffness of the drilled shafts that is so low as to allow the shafts to move along with the moving soil masses;

(e) The sliding soil will continue deform or flow overtop of the secant pile-sheet pile wall which is located at the lower portion of the slope.
4. GETTING STARTED

The UASLOPE 2.3 program contains drop-down menus when it is opened in the Windows environment. These four menus are labeled as “File”, “Run”, “Option”, and “Help”. The functionalities under the each menu are summarized in Figure 1, which also shows a logical flow of the data input process. As can be seen from this figure, the majority of input information is provided through the interface under the “File” menu, which allows for creating an input file through interactive input boxes. The input information needed for defining the problem slope pertains to slope geometry, soil profiles, soil properties, groundwater conditions, and location of the slip surface. The input information needed for defining the drilled shafts and anchors includes the diameter of drilled shaft, center-to-center spacing between the adjacent shafts, location of the drilled shaft/anchor, anchor force, anchor angle, and anchor spacing. At the present time, only the effective analysis method is incorporated into the UASLOPE 2.3 program. Once the input file is created, it should be saved before proceeding to the computation part of the analysis, which is done by selecting “Save as” or clicking the “Auto Save Data + Run” button. The “Options” menu provides path and filename information as well as a chart option by which the color of soil layers, slip surface, and groundwater location can be judiciously customized.

4.1 Installation Path

The default installation path is at “C:\Program Files (x86)\The University of Akron\UA Slope Program 2.3”. After installation, an example input file (i.e., Example.ua3) will be automatically created in this installation path. Meanwhile, an Excel spreadsheet template will be saved in another path at “C:\spile\Template\UASlope_Default.xlsx”. The file path will be automatically created during installation if the path does not exist on the user’s PC.
Figure 1: UASLOPE 2.3 Operational Flow Chart
4.2 Starting the Program

The program can be started by double-clicking the UASLOPE 2.3 icon. The UASLOPE 2.3 main menu will appear as shown in Figure 2. Several functions are available in the drop-down menu under the “File” menu.

![Main Screen showing the Drop-Down under the File Menu](image)

Figure 2: Main Screen showing the Drop-Down under the File Menu

4.3 File Menu

The file menu option, like any Windows-based software, allows the user to create a new file, to import data from an Excel spreadsheet, to open an existing input file (*.ua3), or to save a file that has just been created. In order to be compatible with the previous version (i.e. UASLOPE 2.1), the previous input file (*.uas) of UASLOPE 2.1 can also be opened by UASLOPE 2.3, in which the “Clear Spacing” of drilled shafts in the previous version will be automatically transferred into “Center-to-Center (CTC) Spacing”.
4.3.1 General Information

As depicted in Figure 1 and 2, the main menu is where the general information pertaining to the problem is provided by the user through input boxes in order to create a data file for the case. In the main menu page, as shown in Figure 3 (on the left side of the screen), the user is required to provide basic information related to the project, which includes the number of vertical sections and number of soil layers used to define the slope soil profiles, the system of measurement (English vs. metric) to be used in the analysis, the selection of a total or an effective stress approach, input of soil properties for each soil layer, input of anchor information (such as anchor force, anchor angle, anchor spacing), input of drilled shaft information (including the diameter, center-to-center spacing between adjacent shafts, length, and location), options to indicate if anchors or drilled shafts will be considered in the slope stability analysis, input for auto-calculating the global factor of safety and shaft net force based on different anchor/drilled shaft locations, and the option to automatically save the current data into an Excel spreadsheet for further modification. The program also provides an option to manually input the load transfer factor in lieu of the built-in semi-empirical equations presented in the report (Liang, 2015). On the right side of the screen, the graphic plot of the problem slope is displayed once the coordinates defining the soil profiles are input. An input table is provided so that the user may enter x and y coordinates of the points on each vertical line (section) for each vertical section used to define the slope profile. Pore pressure, as defined either by specified phreatic values or the constant ratio of the pore pressure, may also be entered. Once all necessary input is provided, the data should be saved as a file for subsequent computation.

4.3.1.1 Units of Measurement

UASLOPE 2.3 allows the user to choose between metric and English units, and the selected units will be used throughout the analysis. Table 1 provides a summary of the commonly used units in the metric system and English system in UASLOPE 2.3.
Table 1: Units used in UA Slope 2.1

<table>
<thead>
<tr>
<th>Measurement system</th>
<th>Force [F]</th>
<th>Length [L]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metric</td>
<td>kN</td>
<td>m</td>
</tr>
<tr>
<td>English</td>
<td>lb</td>
<td>ft</td>
</tr>
</tbody>
</table>

Figure 3: General Information Input Window

4.3.1.2 Number of Vertical Sections and Soil Layers

UASLOPE 2.3 requires the user to input the total number of vertical lines (sections) and number of soil layers for defining the geometry, soil profile, and cross section of the slope. To take advantage of this user-friendly method of creating a cross section, a vertical line needs to be
assigned to each breaking point of the boundaries of the slope and the boundaries between different soil layers. The UASLOPE program requires a minimum of two soil layers, and it can only accommodate up to a total of 30 soil layers. At each vertical line (section) with its $x$ coordinate, the corresponding $y$ coordinate for each intersecting point of the vertical line and the left to right lines (defining the soil layer boundaries and slope boundaries) will need to be provided.

### 4.3.1.3 Analysis Method

The program has the capability to run either total or effective stress analysis. However, as mentioned in the report, it is highly recommended that the effective stress approach be used, simply because the load transfer factor was based on the concept of effective stress.

### 4.3.1.4 Soil Properties

As shown in Figure 3, UASLOPE 2.3 requires the user to input the effective shear strength parameters (i.e., cohesion [in psf or kPa] and friction angle [in degrees] and the total unit weight [in pcf or k/m$^3$]) for each soil layer. The maximum allowable layer number is 30 in UASLOPE 2.3.

### 4.3.1.5 Drilled Shaft Information

In the drilled shaft information section, the user is required to input the location of the shaft to be installed within the slope, the shaft diameter, the center-to-center spacing between two adjacent shafts, and the location of the shaft. Also, the user can input the value of the load transfer factor directly using the option to manually input the load transfer factor. The value of the load transfer factor can be anywhere between 0 and 1. This option allows for optimization of the drilled shaft
size, shaft location, and spacing between the drilled shafts for a given unstable slope with a known slip surface in order to achieve the desired target factor of safety (FS) of the slope/drilled shafts system.

4.3.1.6 Anchor Information

In UASLOPE 2.3, a new section of anchor information has been added. The user is required to input the anchor force, anchor angle (measured from horizontal direction), anchor spacing and anchor location. It is noted that the option of anchor location has been integrated into the “X Coordinate”. The range of the anchor angle is from \(-90^\circ\) to \(90^\circ\) (measured from the horizontal plane, positive means counterclockwise and negative means clockwise). In addition, several available options for an anchor and drilled shaft can be selected for stabilizing a failed slope: anchor only, drilled shaft only, or a combination of an anchor and a drilled shaft. In order to design efficiently and reduce construction costs, the value for the anchor spacing \((S_a)\) is not necessarily chosen to be the same as the center-to-center spacing of drilled shaft \((S)\). However, the value of anchor spacing must be chosen as a multiple of the center-to-center spacing of drilled shaft (i.e., \(S_a = n \cdot S\), the integer \(n\geq1\)) when the user analyzes both an anchor and a drilled shaft to stabilize a slope.

Based on finite element analysis of an anchor–drilled shaft/slope system shown in the main report (Liang, 2015), the global factor of safety was not overly affected by considering different anchor parameters when used together with drilled shafts. Therefore, for a conservative design of combined anchor/drilled shafts, the global factor of safety is not influenced by an anchor in UASLOPE 2.3, which means that the existence of anchor only affects the shaft net force for a drilled shaft–anchor/slope system and the resulting shaft deflection. The anchor effect will be considered in the calculation of global factor of safety only if the slope is stabilized by an anchor only (no drilled shafts).
4.3.1.7 “1-Click” Optimization Strategy

In UASLOPE 2.3 program, the enhanced program interface has the capability to auto-calculate a set of cases for different drilled shaft/anchor locations, with the addition of a new input window on the user-friendly interface to allow for inputting the following: (a) initial location of the drilled shaft/anchor \(X_{\text{min}}\), (b) ending location of the drilled shaft/anchor \(X_{\text{max}}\), and (c) location increment \(X_{\text{Delta}}\). The optimization strategy is capable of dealing with five different circumstances: drilled shaft only (automatic load transfer factor), drilled shaft only (manually defined load transfer factor), anchor only, anchor and drilled shaft (automatic load transfer factor), and anchor and drilled shaft (manually defined load transfer factor). If the engineer chooses “Auto = off”, UASLOPE 2.3 will calculate the factor of safety and shaft net force one time for the specified drilled shaft/anchor location. If the engineer chooses the “Auto = on” option, the parameters (including initial location of the drilled shaft/anchor, ending location of the drilled shaft/anchor and the horizontal location increment) need to be defined. After running the program, UASLOPE 2.3 will automatically calculate the factor of safety and the shaft net force based on different shaft/anchor locations. All calculation results will be exported into a new Excel spreadsheet, from which a figure with the relationship between the shaft net force and the shaft location, as well as a figure showing the relationship between the factor of safety and the shaft location, will be automatically generated to allow the engineer to view the results more efficiently and intuitively. The newly generated Excel spreadsheet output can be found in the file path “C:\spile\Excel_Results”. This function can shorten the design time and prevent potential human input errors. In addition, the calculation results for the ending location of the drilled shaft will be displayed on the current UASLOPE 2.3 program interface.

It is noted that the initial location of the drilled shaft (i.e., \(X_{\text{min}}\)) must be no less than the initial x coordinate of the slip surface, and the ending location of the drilled shaft (i.e., \(X_{\text{max}}\)) must be less than the ending x coordinate of the slip surface. The location increment (i.e., \(X_{\text{Delta}}\)) can be chosen as any value between 0 and the value of \((X_{\text{max}} – X_{\text{min}})\). In order to review all the results based on different shaft/anchor locations, the “Auto Save Data” option must be selected when the user performs the “1-click” optimization strategy.
4.3.1.8 Save Input Data

The input data can be saved into a *.ua3 file by using “File ▶ save as...” option. Also, all the data shown on the interface of UASLOPE 2.3 can be exported into an Excel spreadsheet by checking “Auto Save Data” near the “Run” button, as shown in Figure 2. When the user selects the option of “Auto Save Data”, an Excel program will be automatically opened in the system background after the user run the program. It should be noted that the total running time of UASLOPE 2.3 will depend upon the current system configuration of the user’s PC for processing the Excel program (i.e. open Excel ▶ save data ▶ close Excel). Therefore, the real calculation time will vary from seconds to minutes. The program running time can be significantly decreased when the user unchecks the “Auto Save Data” option.

4.3.1.8 Slope Profile Vertical Sections

The user is required to input the x and y coordinates defining the geometry and soil layers of the slope. The xi value for each vertical line (section) should be entered in an ascending order from left to right, and the yi value of each intersection point on a particular vertical line should be entered in the order of from the top layer to the bottom one. The definition of the x-y coordinate system used by the UASLOPE 2.3 program is shown in Figure 4, in which the origin of the x-y coordinates is at the upper left corner of the screen; the x-value increases as it moves to the right and the y-value increases as it moves down. It is very important that the slope should be represented in such a way that the slope is sloping down from left to right, as shown in Figure 4.

Also, the user is required to input the “Coordinates of the crest” and the “Coordinates of the toe.” These coordinates should be estimated based on the slope profile section and will be used to calculate the slope angle.
4.3.1.9 Pore Water Pressure

UASLOPE 2.3 program allows the user to choose from three different pore water pressure options: (1) no pore pressure, (2) constant pore pressure ratio, and (3) specified groundwater surface.

The groundwater surface is defined by the x-y coordinate of the points selected. The x-values should be input in an ascending order. As shown in Figure 5, the user can set the number of points (up to a maximum of 50 points), add a point, or delete a point by right-clicking in the defined box in the pore water pressure portion of the screen.
4.3.1.10 Slip Surface

The user needs to input the total number of points (maximum of 50 points) along the slip surface by right-clicking in the slip surface box as shown in Figure 5. Once this number is defined, the x-y coordinates of each selected point should be typed in accordingly. Again, the x-values of the selected points should be input in an ascending order (i.e., in the direction from left to right).

4.3.1.11 Chart (Double-Click for More Options)

By double clicking on the chart in the “Chart (Double-Click for More Options)” section of the interface, “Chart View” window appears and allows the user to see the soil profile with or
without “layers”, “pore pressure”, “slip surface”, and “shaft”. In addition, this screen provides an option for the user to either “zoom in” or “zoom out.”

4.4 User Instruction for Importing/Exporting Tabular Data with Excel Spreadsheet

A function to ensure compatibility with imported/exported spreadsheet data has been added in UASLOPE 2.3, which can be found from the upper tab of the program interface: “File” → “Import Excel”. In UASLOPE 2.3, the engineer not only can import all the design data from a pre-defined Excel spreadsheet to a blank UA Slope program interface but also can export all the design data (i.e., slope profile, soil parameters, slip surface, phreatic surface, drilled shaft parameters, anchor parameters, etc.) and design results (i.e., factor of safety and drilled shaft net force for different drilled shaft locations) into a new Excel file. The newly generated Excel spreadsheet output will be saved in the file path “C:\spile\Excel_Results.” It is noted that the user must follow the provided Excel template to modify/edit the input data. In order to prevent the user from accidently deleting the Excel template, a new Excel spreadsheet template will be automatically generated each time the user runs the program; the Excel template is located in the path “C:\spile\Template”. An example Excel spreadsheet template is shown in Figure 6.

Figure 6: Typical Excel Spreadsheet Input of UASLOPE 2.3
The engineer can easily edit the input data in the cell highlighted in yellow in Figure 6. In the UASLOPE 2.3 program, the engineer can set the input data either directly from the program interface or from the provided Excel template.

### 4.4.1 Explanation of Terminology used in the Excel Spreadsheet (Import)

#### 4.4.1.1 Control data

On the interface of UASLOPE 2.3 program, the control options (such as “English” units or “Metric” units, “total stress” or “effective stress”, “without” drilled shaft or “with” drilled shaft, etc.) can be set by a simple mouse click. Nevertheless, in the Excel template, the above options can be represented as a controlling number. For example, the ID_Unit can be set as “0” if English units will be employed or set as “1” if metric units will be used. All the explanations of the control data are listed in the following.

- **ID_Unit**: 0 = English, 1 = Metric;
- **ID_Method**: 0 = Total Stress, 1 = Effective Stress;
- **ID_Pore**: 0 = No Pore Pressure, 1 = Constant Ratio, 2 = Specified Phreatic Surface;
- **Section Num**: Section number;
- **Soil Layer Num**: Soil layer number;
- **ID_Shaft**: 0 = No Shafts; 1 = With Shafts
- **ID_Eta**: 0 = Automatically calculated load transfer factor (Eta), 1 = Manually defined load transfer factor (Eta).
- **ID_Anchor**: 0 = No Anchor; 1 = With Anchor
- **Automatically Shaft Location**: 0 = Off; 1 = On.

It is noted that the drilled shafts will not be involved in the calculation of the factor of safety when the ID_Shaft is set as “0” (i.e., no shafts), no matter which number is indicated in the ID_Eta setting. In other words, ID_Shaft must be set as “1” if the drilled shaft needs to be involved for both auto-calculate load transfer factor and the manually defined load transfer factor.
All the control data have been circled in Figure 7.

![Control Data in Excel Spreadsheet](image)

**Figure 7: Control Data in UASLOPE 2.3**

### 4.4.1.2 Drilled shaft data

In the template Excel spreadsheet, the user can input the drilled shaft parameters in cells E3 to O6. As displayed in Figure 8, the optimization strategy of drilled shaft location can be set as “Auto = on/off” (i.e., in the Excel file, “0” = off, “1” = on). If the auto shaft location is set “on”, the factor of safety and drilled shaft force will be calculated based on different drilled shaft locations, which can be defined by the initial location of drilled shaft ($X_{min}$), the ending location...
of drilled shaft ($X_{\text{max}}$) and the location increment ($X_{\Delta}$). The optimization design strategy has already been elaborated in Section 4.3.1.7.

![Figure 8: Drilled Shaft Data in UASLOPE 2.3 and Excel Spreadsheet](image)

**4.4.1.3 Anchor data**

The anchor information in the Excel spreadsheet can be edited from cell $Q3$ to $T5$, including anchor force, anchor angle and anchor spacing. In the example shown in Figure 9, the anchor location has been integrated into the “$X$ Coordinate” under the drilled shaft parameter.
4.4.1.4 Slope profile and soil properties

The slope profile in the Excel spreadsheet can be set from cell C13 to cell AZ44, and the soil properties can be set from cell C50 to cell E79. In the Excel spreadsheet, the allowable slope section is set as 50 and the allowable soil layer is set as 30, which are sufficient for normal engineering design purposes. The definition rule of input in the Excel spreadsheet is the same as on the program interface, which can be expressed in Figure 10. It is noted that the engineer can easily edit the Excel spreadsheet by copying/pasting data or by inserting/deleting a soil layer or a slope section in the Excel spreadsheet during design.
4.4.1.5 Other parameters

The coordinates of the slope crest and toe, the phreatic surface, and the slip surface can be defined in the Excel spreadsheet from cell I50 to cell AL65. The allowable number of input points for both the phreatic surface and the slip surface are set at 30. The relationships between the program interface and the corresponding Excel tabular data are presented in Figure 11.
4.4.2 Explanation of Terminology used in the Excel Spreadsheet (Export)

After the user selects “Auto Save Data” and clicks the “Run” button, the results will be automatically saved into an Excel file. The output results include the factor of safety and the drilled shaft force (in lbs and kips), which are saved in the “EXPORT” worksheet in the Excel file. In addition, two figures (one showing the relationship between the factor of safety and the drilled shaft offset, and the other showing the relationship between drilled shaft force and drilled shaft offset) will be automatically placed on the screen in a position that is close to the calculation results. The engineer can use these results to analyze slope stability based on different drilled shaft locations and can easily copy/paste all results and/or figures into the engineering report. The file path of the Excel spreadsheet with the results is found at “C:\spile\Excel_Results”, and the filename for the Excel spreadsheet is based on the current PC
time. For example: “UASlope_20150302_231843_130” means “2015/03/02, 23:18:43”, the last three digits “130” represents milliseconds. The explanation of the output results is illustrated in Figure 12.

![Figure 12: Explanation of Output Results](image)

4.5 Run Menu

The “Run” feature is used to execute an analysis an existing data file. The user can select whether or not to consider the drilled shaft/anchor in the analysis. The user can either click the “Run” button at the bottom left corner of the screen (as shown in Figure 13) or choose the
Execute option under the “Run” drop-down menu. The results will appear in the “Calculated Result” text boxes on the same screen.

Figure 13: Run Menu

4.6 Options Menu

The “Options” menu provides information about path and file names. In addition, as shown in Figure 14, “Chart options” can be selected from the “Options” menu. This option allows the user to change the colors of the soil layers, slip surface, and ground water surface. By double-clicking on the chart, the user will be able to turn on/off the layers, slip surface, and groundwater surface, as well as to change the color of layers.
Figure 14: Chart Option in the Option Menu
5. ILLUSTRATIVE EXAMPLE

The primary purpose of this illustrative example is to show how to generate a data file for subsequent computation by the UASLOPE 2.3 program. It is, however, not intended to demonstrate the design procedure.

5.1 General Description of the Example Slope

The slope geometry for this illustrative example is shown in Figure 15. This example considers a 35-foot-high slope with a slope of 40 degrees. The soil in the slope consists of two different soil layers: the main slope body belongs to Soil Layer I, and the firm stratum below the elevation of the toe belongs to Soil Layer II. The groundwater table elevation is assumed as shown in Figure 15. The soil properties for the two different soil layers are summarized in Table 2. With the given slope geometry, soil profile, and soil properties, the factor of safety of this slope was calculated as 1.025 by using UASLOPE 2.3.

Figure 15: The Slope Geometry, Soil Profile, Slip Surface, and Groundwater Table for the Illustrative Example
Table 2: Soil Properties for the Two Soil Layers in the Illustrative Example

<table>
<thead>
<tr>
<th>Soil</th>
<th>Cohesion (psf)</th>
<th>Friction Angle (Degree)</th>
<th>Unit Weight (pcf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>200</td>
<td>11</td>
<td>115</td>
</tr>
<tr>
<td>II</td>
<td>500</td>
<td>15</td>
<td>125</td>
</tr>
</tbody>
</table>

5.2 UASLOPE 2.3 Program

To see the input file for the illustrative example, the user can open the file named “Example.ua3” that is provided on the UASLOPE 2.3 installation disc. This example is further explained below.

5.2.1 General Information, Slope Geometry and Slip Surface Specifications

The input and output for the slope considered in the illustrative example may be seen on the screen shown in Figure 16. The following should be noted regarding the analysis for the example slope.

- English units are used for this analysis (force is reported in lb, and length is reported in ft).

- Four vertical sections are needed to define the boundaries in the example slope shown in Figure 15.

- Two soil layers are considered: Soil Layer I for soil in the slope body and Soil Layer II for soil in the foundation.
- A total of eight (8) points along the identified slip surface are entered to represent the location of the slip surface.

- The groundwater table is defined by two points.

- The effective stress approach is used for this analysis.

- As a starting point, the drilled shaft is selected at X = 60 ft. The initial selection of drilled shaft dimensions for trial design is as follows: the drilled shaft diameter = 4 ft and the center-to-center spacing between adjacent drilled shafts = 8 ft. Anchor information for the trial design is as follows: anchor force = 50 kips, anchor angle = 30°, and anchor spacing = 8 ft.

- The x-coordinates for the four (4) vertical sections to represent the slope profile should be input in an ascending order in the first row of the grid provided for the slope profile specifications, as shown in Figure 16. The y-coordinates for each layer from top to bottom should be input corresponding to each x-coordinate entered. (See Figure 16 for the values for x and y that are used in the analysis).

- From Table 2, material properties are input in the grid provided for the soil properties. The first row represents the material properties for the first (upper) soil layer, the second row represents the material properties for the second (lower) soil layer, and so on.

- Once the input data is completely filled in, the data should be saved as a file (i.e. *ua3 file or Excel spreadsheet file) before proceeding with the computation. It is good practice to first run the option to calculate with no drilled shaft and with no anchor so that the accuracy of the defined slope geometry, soil profile, and soil properties can be ascertained. Figure 16 shows the computed factor of safety for the defined slope problem as 1.025. After a satisfactory run with an option without a drilled shaft or anchor, the program can be run with the option to consider drilled shafts and anchors. The factor of safety and the net force on the drilled shaft for the anchor–shaft/slope system will appear in the “calculated result” box on the same screen, as can be seen in Figure 17.
Figure 16: Input and Output for the Illustrative Example (Slope Only)

Figure 17: Input and Output Result when Considering both Anchor and Drilled Shaft Option
The existence of anchor can reduce the shaft net force. However, if the anchor spacing is bigger than shaft spacing (such as 2 times or 3 times of shaft spacing), net force on the drilled shaft which is located between two adjacent anchors may not be affected significantly by the existence of anchor. For a conservative structural design, it is recommended that the net force on drilled shafts which are between two adjacent anchors will be calculated without anchor effect. In other words, the existence of anchor only reduces the net force of conjoint drilled shaft. Also, the default upper boundary of anchor spacing is equal or less than 3 times of drilled shaft spacing in UASLOPE 2.3 program.

The user can proceed in the analysis by trying different drilled shaft diameters, shaft spacing, locations, anchor force, anchor angles and anchor spacing so that all design requirements and constructability issues can be evaluated. For example, several runs were carried out with a shaft diameter of 4 ft and a center-to-center spacing between the shafts of 8 ft, while varying the location of the drilled shafts from X = 30 ft to X = 90 ft in 5-ft increments. The resulting factor of safety and the net force on the shaft for each considered shaft location are tabulated in Table 3 and plotted in Figures 18 and 19. The corresponding Excel spreadsheet input has been illustrated in Figure 20.
Figure 18: Plots of Factor of Safety versus Drilled Shaft Offset for the Illustrative Example

Figure 19: Plots of Net Shaft Force versus Drilled Shaft Offset for the Illustrative Example
Table 3: Values of Factor of Safety and Shaft Net Force of an Anchor-Shaft/Slope System for Different Shaft/Anchor Locations

<table>
<thead>
<tr>
<th>X (feet)</th>
<th>Offset (feet)</th>
<th>FS</th>
<th>Force per shaft (kips)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0</td>
<td>1.02</td>
<td>0.0</td>
</tr>
<tr>
<td>35</td>
<td>5</td>
<td>1.05</td>
<td>0.4</td>
</tr>
<tr>
<td>40</td>
<td>10</td>
<td>1.12</td>
<td>16.6</td>
</tr>
<tr>
<td>45</td>
<td>15</td>
<td>1.27</td>
<td>51.3</td>
</tr>
<tr>
<td>50</td>
<td>20</td>
<td>1.46</td>
<td>83.8</td>
</tr>
<tr>
<td>55</td>
<td>25</td>
<td>1.82</td>
<td>128.2</td>
</tr>
<tr>
<td>60</td>
<td>30</td>
<td>2.24</td>
<td>162.0</td>
</tr>
<tr>
<td>65</td>
<td>35</td>
<td>2.35</td>
<td>165.3</td>
</tr>
<tr>
<td>70</td>
<td>40</td>
<td>1.92</td>
<td>126.9</td>
</tr>
<tr>
<td>75</td>
<td>45</td>
<td>1.52</td>
<td>80.3</td>
</tr>
<tr>
<td>80</td>
<td>50</td>
<td>1.19</td>
<td>21.3</td>
</tr>
<tr>
<td>85</td>
<td>55</td>
<td>1.07</td>
<td>0.8</td>
</tr>
<tr>
<td>90</td>
<td>60</td>
<td>1.02</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Figure 20: Excel Spreadsheet Input for the Illustrative Example
6. GENERAL COMMENTS ON USING UASLOPE 2.3

- The minimum number of soil layers considered with UASLOPE 2.3 should be two (2) layers, while the maximum number of soil layers is thirty (30).

- Only one single row of spaced drilled shafts/anchor can be considered.

- The point of origin for the coordinate system used by UASLOPE 2.3 is at the upper left corner.

- The downslope direction of the slope should be defined by convention (i.e., from left to right).

- Always ensure that the end points of the slip surface (i.e., the initiation and exit points) match with the specified boundaries of the slope.

- Always start the analysis without considering the drilled shaft/anchor on the slope in order to confirm that the correct input was provided in creating the input file.
7. BIBLIOGRAPHY

