Design Method for Slide-Stabilizing Micropile Walls

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ABSTRACT

A design method is presented for slope stabilization involving the use of micropiles extending through the sliding mass into more stable material. This type of wall typically consists of a line of micropiles placed into the soil mass at alternating batter angles. The micropiles are fixed at the ground surface by means of a concrete cap beam running the length of the wall, effectively creating a structural 'A-frame' to resist landslide forces. Wall design parameters include size and location of the cap beam, micropile spacing, batter angles, lengths, diameters, and structural design. Current design methods presented in the literature and in the FHWA Reference Manual for Micropiles are reviewed briefly and found to have several shortcomings. In particular, the treatment of individual micropiles as free-standing structural elements subjected to lateral loading at the slide plane and concentrated load at the pile head does not adequately account for the structural interaction that occurs due to the micropiles being connected at the cap beam. In addition, studies of instrumented micropile walls described in the literature indicate that the resistance to sliding contributed by micropiles depends more upon mobilization of axial resistance of the micropiles than it does upon their bending resistance. These observations suggest a simple design method in which the micropile wall is modeled and analyzed as a structural frame, and in which axial force mobilized in the micropiles controls the design of the structure and provides a more realistic representation of wall performance.

INTRODUCTION AND BACKGROUND

When used in a slide stabilizing wall system, micropile walls consists of multiple micropiles battered alternately upslope and downslope and connected at the surface by means of a concrete capping beam running the length of a landslide as illustrated in Figure 1. The micropiles extend through the slide mass into competent soil or rock beneath the slide.

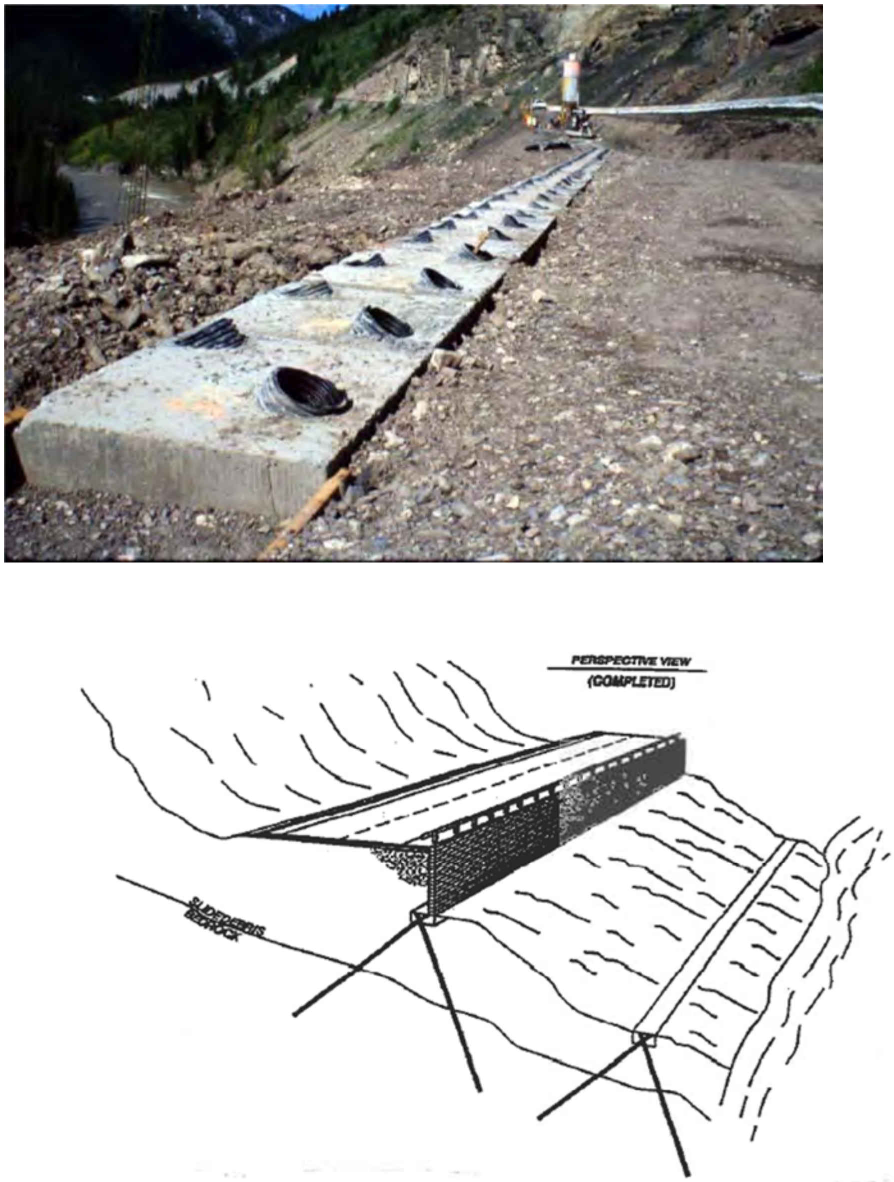

Figure 1. General Layout of Micropile Walls

There is currently no consensus regarding the proper design approach for micropile wall systems. The most widely-cited procedure is described in the FHWA/NHI Micropile Design Manual (Sabatini et. al., 2005). Back analysis of a failed slope is used to determine the additional resistance to sliding that must be provided to achieve a target factor of safety. The micropile wall trial design is evaluated against the required resistance by analyzing individual micropiles for axial, shear, and bending strength assuming that each micropile acts as a vertical, free-headed pile. Design loads are determined by modeling soil layers as equivalent springs in a pile *p-y* analysis. Landslide forces are rotated and micropiles are loaded using an equivalent concentrated load acting at the surface. Besides being difficult to implement in practice, it is the authors' observation that the limiting factor that determines micropile design with this approach is the bending resistance of the micropile. However, the authors' experience, as well as that of others as reported in the literature, suggests strongly that micropiles used in this type of system undergo only small bending stresses and instead provide resistance through mobilization of axial forces. For example, consider the findings of three studies in which slide stabilizing micropiles were instrumented to determine axial and bending stresses in the micropiles. The following quotes are taken directly from the conclusions of three reports based on field measurements of full-scale micropile walls:

<u>Littleville, Alabama, Brown and Chancellor (1997)</u>

"the stabilizing effect from the piles is more closely related to axial forces and the batter angles than was expected in the original design procedure"
"actual bending moments appear to be considerably lower than those predicted by the design . . . axial capacity of the micropiles would be the limiting factor at failure".

<u>Blue Trail, Wyoming, Hasenkamp and Turner (2000)</u>

" . . axial tension and compression appears to contribute almost all of the resistance to sliding . . . Design procedures for future projects should focus on utilizing the axial capacity of micropiles, rather than their bending capacity"

<u>Richfield Township, Ohio, Liang and Geiger (2002)</u>

"The presence of such low moments implies that the orientation of the minipiles was optimally determined and that minipiles should be sized primarily for axial load and shear forces"

Based upon observed field behavior of instrumented case histories, it is concluded that the micropiles resist landslide forces primarily through axial tension and compression. This is due to the presence of the capping beam which causes micropiles to behave like a structural frame. By modeling micropiles as vertical, free-headed piles, bending moment predictions are much higher than those observed in instrumented full-scale installations. Also, modeling landslide forces as concentrated load acting at the tops of the micropiles is not a reasonable assumption of soil loading conditions. A more accurate model would involve landslide forces being distributed along the entire length of the micropile wall.

PROPOSED DESIGN METHOD

A relatively simple model that accounts for the structural response of micropiles subjected to moving ground is proposed. Because the micropile wall is a structural system, a simple frame model provides the ability to account for structural interaction between the upslope and downslope micropiles connected at the cap wall (Figure 2).

Landslide forces are modeled as a distributed load acting in the direction of the slide and applied to the upslope side of the frame. The magnitude of load is determined by the additional resistance required to achieve a target factor of safety. Structural analysis of the frame can be used to determine an upper-bound magnitude of axial load transferred to each micropile. Field observations, noted above, indicate that axial loading of micropiles is the primary mechanism of resistance in response to slide movements. Micropiles can then be designed structurally and geotechnically to resist the calculated axial loads.

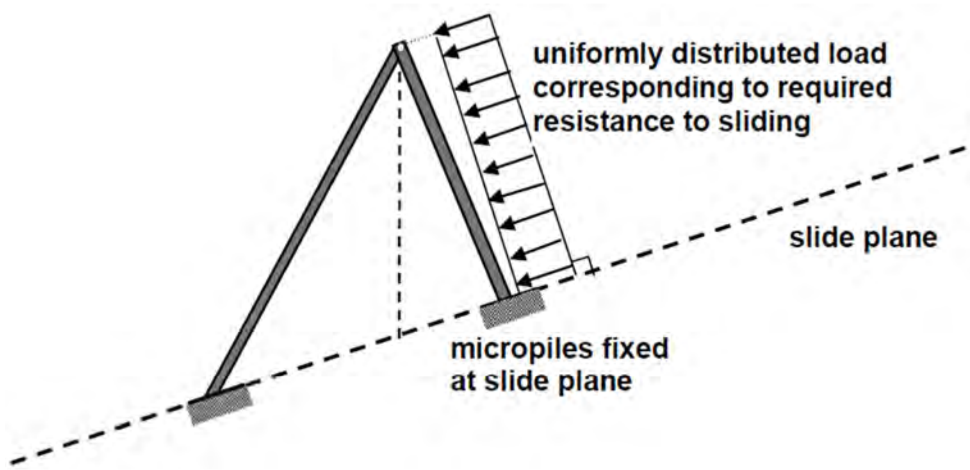

Figure 2. Plane frame model and assumed loading of micropile wall.

The proposed method involves the following steps:

1. Determine the required wall resistance to achieve the target FS determined by slope stability analysis.
2. Select trial micropile layout (location, spacing, batter angles).
3. Treat micropile/cap beam system as a structural frame and apply the required resistance as a uniformly distributed load acting downslope and parallel to the slide surface. This step is used to determine axial loads transferred to the micropiles.
4. Check structural design of micropiles for axial load.
5. Perform geotechnical design of micropiles for axial load.

Step 1. Required Wall Resistance

For an active landslide, limit equilibrium methods typically are used to evaluate the driving and resisting forces that exist within an unstable slope. This is carried out by conducting a back analysis of the unstable slope, assuming an existing factor of safety equal to unity, using a limit equilibrium approach (*e.g.*, see Duncan, 1996). Using data from site geotechnical investigations and laboratory testing results, the geometry of a site is modeled as closely as possible. A target factor of safety against sliding, to be achieved by constructing one or more micropile walls, is selected. Target factors of safety for highway-affecting landslides vary between 1.25 and 1.5, depending upon factors that include the size of the slide, importance of facilities that may be affected, risk to the traveling public, and the cost of remediation (Holtz and Schuster, 1996). A value of 1.3 is typical and often is adequate for slopes under static conditions but the final decision rests with the design engineer. In areas where seismic activity is expected, lower target factors of safety for the seismic case between 1.0 and 1.1 are normally used. The additional force to achieve the desired factor of safety, expressed in units of force per unit of wall length, is calculated by:

$$FS = \frac{(R_e + R_m)}{D_e} \quad (1)$$

or $$R_m = (FS \times D_e) - R_e \quad (2)$$

FS = target factor of safety against sliding
R_e = existing resisting force along the slide plane
R_m = required micropile wall resistance per unit of slope
D_e = existing driving force present within the slope

In this approach, a simplifying assumption is made that the required resisting force is the same across the entire slope. For slides with large differences in cross section or driving/resisting forces, designs may warrant multiple wall profiles along the wall length.

Step 2: Trial Micropile Layout

The three primary considerations for a trial layout are; (1) location of the micropile wall with respect to the toe and scarp of the slide, (2) spacing between micropiles, and (3) batter angles of upslope and downslope micropiles. Recommendations for these considerations are given below.

Location of the Micropile Wall. Location of the micropile wall relative to the top and bottom of the slide must first be established. According to Howe (2010), the optimum location for designs incorporating a single micropile wall for landslides that can be approximated by a circular failure surface appears to be between 50% and 75% up the slope from the toe. However, the upper end of this range seems excessively high along a slope and provides opportunity for soil below the wall to continue sliding. The upper sections of many landslides are often difficult to access. This optimum location may vary for slopes involving planar slip surfaces or block failures existing directly between weak soil and rock layers. Walls should generally be located downslope from large surcharges or sources of slope live load (roads, railways, embankments, etc.). Long slides, such as that at Blue Trail (Hasenkamp and Turner, 2000), have used multiple walls effectively to provide resistance at several locations along the slide.

Micropile Spacing. In addition to providing structural resistance, micropile spacing is chosen to prevent plastic flow of soil between micropiles while still providing the greatest efficiency. Greater spacing results in fewer micropiles and decreased installation costs, but the need for increased section strength properties. It is up to the designer to perform an adequate cost comparison analysis. Based upon published case studies cited above, it appears that designs involving micropile pairs spaced between 0.8 m and 1.1 m (2.5 to 3.5 feet) on center (0.40 - 0.55 m, or 1.25 - 1.75 feet between individual micropiles) have worked well. Plastic flow of soil between micropiles does not appear to have been a problem when using these spacing intervals but should be carefully analyzed for larger spacing intervals or if weak soil is present. A method for analyzing the potential for plastic flow of soil around piles is discussed in the NHI Micropile Manual (Sabatini, et al., 2005) using theory presented by Ito and Matsui (1975).

Batter Angles. Batter angles for micropiles are chosen based upon maximizing structural geometry while minimizing the required installation lengths. Upslope micropiles battered between 25 and 35 degrees from vertical have worked well in past designs and provide a starting point for preliminary layouts. Downslope micropile batters should be examined more closely to prevent incorporating excess length. Using steeper downslope batter angles requires greater installation lengths to penetrate the slide plane and provide adequate geotechnical resistance in the competent material below. This effect increases with steeper failure surfaces. For the presented design method, it is recommended to try initial downslope batter angles close to vertical, say 5 to 10 degrees downslope. If structural support cannot be achieved, the downslope batter angle is gradually increased until the necessary strength requirements are met.

Step 3. Analysis of Micropile Loads

After the trial layout has been selected, loads transferred to the micropiles by the sliding soil mass are calculated. The additional required force per unit of slope (R_m), determined by limit equilibrium slope stability analysis (Eq. 2), is multiplied by the trial spacing of the micropile pair, giving the resisting force that each micropile pair must be capable of providing, as follows:

$$R_{m-pair} = R_m \times S_{m-pair} \quad (3)$$

$R_{m\text{-pair}}$ = resistance provided by each micropile pair
R_m = required micropile wall resistance per unit of slope
$S_{m\text{-pair}}$ = center to center spacing between micropile pairs

The total force resisted by each micropile pair is then assumed to be applied uniformly over the length of the upslope micropile above the slide plane. By dividing by the length of the upslope micropile between the ground surface and the point at which the micropile crosses the slide plane, an equivalent distributed load (w) can be calculated. The length can be determined from the problem geometry and using output from slope stability software. Application of a uniform load distributed over the length of the upslope micropile represents landslide forces more realistically than a concentrated load acting at the slide plane. Based upon analysis of case histories by Halvorsen (2012), a uniform distribution of the earth pressure provides a conservative estimate of design axial loading of the micropiles. The magnitude of the uniformly distributed load (w) is calculated by:

$$w = \frac{R_{m-pair}}{L_{m-slide}} \quad (4)$$

$L_{m\text{-}slide}$ = length of upslope micropile above the slide plane

The equivalent uniformly distributed load (w) is applied to the frame on the upslope micropiles in a direction parallel to the failure surface of the slide, as illustrated in Figure 2. For circular slide surfaces, a straight line is drawn between the points where the upslope and downslope micropiles intersect the slide plane and loads are applied parallel to this line.

Structural analysis under the uniformly distributed loading is carried out to calculate the axial loads that develop within the micropiles. As previously discussed, case studies have shown that axial forces develop first and are the limiting strength property for design of this system. Shear and bending are secondary.

Structural analysis software is convenient for modeling the simple frame and equivalent loads. It is recommended that micropiles be connected rigidly at the top to account for the presence of the concrete capping beam. The cap beam (node at micropile connection) should be allowed to displace as the frame is loaded. This accounts for the observation that some displacement needs to occur in order for micropiles to develop full resistance to sliding. Micropiles should also be fixed below the slide plane using an equivalent depth of fixity to represent displacement of soil near the slide plane. The depth of fixity has been found to not greatly affect axial load development within the model but does provide a more realistic representation compared to fixing micropiles directly at the slide plane. Depths of fixity between two and four micropile diameters are recommended for most soil situations where competent materials exist below the slide plane, but this should be evaluated on a project-specific basis. For micropiles socketed into rock, smaller depths of fixity can be used to account for the higher restraining effect of rock compared to soil, but this can also vary depending on the degree of fracturing and weathering at the top of rock. It should be noted that the distributed load is applied only to the length of the micropile above the slide plane and is not transferred to the extra length which results from using a depth of fixity. The structural analysis provides the axial loads transmitted to the micropiles resulting from loading the wall with a uniformly distributed load that is equivalent to the structural resistance required of the wall. Micropiles are then designed to carry these loads structurally and geotechnically.

When a uniform load is applied along the length of an upslope micropile within the slide, structural analysis predicts significant development of bending moments within the micropile. However, field observations show that this is not the case or that the effect is significantly reduced. This could be due to soil resistance against the opposite side of the micropile which opposes the load and limits deflections and bending. In the simplified design procedure presented herein, the predicted bending moment from structural analysis is neglected, based on the assumption that axial load controls.

Step 4. Structural Design

Structural design of the micropiles includes choosing the diameter and reinforcement necessary to resist the axial tensile and compressive loads determined from structural analysis. An LRFD approach is best suited to provide adequate levels of safety within designs. A load factor of 1.5 is recommended.

The factored resistance provided by micropiles is calculated using the equations for tensile and compressive strength shown below. For tensile resistance calculations, grout within the micropiles is assumed to have cracked and does not provide strength to the system. Thus, only properties of the reinforcing steel are used. For compressive resistance the grout is included. Recommended equations for allowable stress design are presented by Bruce, et. al. (2005).

Factored tensile resistance

$$P_t = 0.90 f_y A_s \tag{5}$$

P_t = factored tensile resistance of micropile
f_y = yield strength of reinforcing steel
A_s = cross section area of reinforcing steel

Factored compressive resistance

$$P_c = 0.75(0.85 f_c' A_{grout} + f_y A_s) \tag{6}$$

P_c = factored compressive resistance of micropile
f'_c = compressive strength of grout
A_{grout} = net cross sectional area of grout

Step 5. Geotechnical Design

Geotechnical design involves providing adequate micropile length below the slide plane to resist the unfactored tensile and compressive forces determined through structural analysis. End bearing resistance is generally neglected and all resistance is assumed to be derived from side resistance at the micropile - soil/rock interface. For landlside stabilization, all resistance must be derived from competent soil or rock beneath the slide plane. For preliminary design presumptive bond stress values are adequate, for example as shown in Table 1 (Bruce et al., 2005). Ultimate bond stress should be divided by a factor of safety of 2.0 to determine allowable bond stresses used for design. For actual field bond stresses between the grout and soil interface, a predesign load test is recommended. The required micropile length below the slide plane to provide geotechnical stability can then be calculated by:

$$L_{reqd} = \frac{P}{f_{all}\pi D} \tag{7}$$

L_{reqd} = required length of micropile beneath slide plane
P = axial force from structural analysis output
D = outside diameter of micropile
f_{all} = allowable bond stress between micropile and soil/rock interface

Table 1. Presumptive Values of Ultimate Bond Stress (Bruce et. al., 2005)

SOIL / ROCK DESCRIPTION	GROUT-TO-GROUND BOND NOMINAL STRENGTHS (KPA)			
	TYPE A	TYPE B	TYPE C	TYPE D
Silt & Clay (some sand) (soft, medium plastic)	35-70	35-95	50-120	50-145
Silt & Clay (some sand) (stiff, dense to very dense)	50-120	70-190	95-190	95-190
Sand (some silt) (fine, loose-medium dense)	70-145	70-190	95-190	95- 240
Sand (some silt, gravel) (fine-coarse, med.-very dense)	95-215	120-360	145-360	145-385
Gravel (some sand) (medium-very dense)	95-265	120-360	145-360	145-385
Glacial Till (silt, sand, gravel) (medium-very dense, cemented)	95-190	95-310	120-310	120-335
Soft Shales (fresh-moderate fracturing, little to no weathering)	205-550	N/A	N/A	N/A
Slates and Hard Shales (fresh-moderate fracturing, little to no weathering)	515-1,380	N/A	N/A	N/A
Limestone (fresh-moderate fracturing, little to no weathering)	1,035-2,070	N/A	N/A	N/A
Sandstone (fresh-moderate fracturing, little to no weathering)	520-1,725	N/A	N/A	N/A
Granite and Basalt (fresh-moderate fracturing, little to no weathering)	1,380-4,200	N/A	N/A	N/A

Type A: Gravity grout only
Type B: Pressure grouted through the casing during casing withdrawal
Type C: Primary grout placed under gravity head, then one phase of secondary "global" pressure grouting
Type D: Primary grout placed under gravity head, then one or more phases of secondary "global" pressure grouting

After construction of the micropiles is complete, a proof test should be performed to confirm the ability of the micropiles to carry the design load.

Following the procedures described above, it will become apparent to the design engineer whether or not a micropile wall system will work for a specific situation. If a design spacing between individual micropiles greater than 0.4 m (1.25 ft) cannot be achieved using cross sectional properties typical for micropiles, a micropile wall may not be the most suitable stabilization system and other options should be explored. If micropile resistances and geometry appear reasonable, then the above procedures should be reiterated with any desired changes to check the final design. Upon completion of the final design, it is recommended that a slope stability analysis be performed for the portion of the slope below the micropile wall to determine the factor of safety against sliding and the location of any potential failure surfaces.

APPLICATION OF THE PROPOSED METHOD

Four published case histories involving instrumentation and monitoring of micropile walls were evaluated in order to compare designs obtained using the procedure described in this paper to (a) the original design, which in each case was consistent with the approach presented in the FHWA manual (Sabatini, et al. 2005) and (b) to the as-built conditions. Details of this study are presented in Halvorson (2012) and are beyond the scope of this paper. The four case histories are documented in Brown and Chancellor (1997), Hasenkamp and Turner (2000), Liang and Geiger (2002), and Bruce et al. (2004). Results can be summarized as follows.

By using the proposed method with design parameters from the original reports, it is shown that for all four cases the original design provides adequate support to meet global stability requirements, for both static and seismic loading. This is critical to validating the proposed method since field observations have shown that all of the presented case histories have proved successful at stabilizing their respective slopes. Second, the design spacings, lengths, and structural properties of the micropiles obtained using the proposed design procedure are in reasonable agreement with the as-built characteristics of the four projects. In all cases, the structural resistance of the micropiles exceeds the required values, suggesting that more cost-effective designs are possible.

SUMMARY AND CONCLUSIONS

Using observations from four documented case histories, a new design procedure for slide stabilizing micropile walls is presented. This procedure accounts for the mobilization of axial forces along micropiles which appears to be the controlling factor in micropile wall design. The design steps are:

1. The required wall resistance that is necessary to achieve the target FS is determined through slope stability analysis. This should be performed using a back analysis technique to find soil strength parameters. When the final soil properties have been adjusted to give a slope factor of safety close to one, the driving and resisting forces within the slide are determined using a limit equilibrium approach.

2. A trial micropile layout is selected for initial design. Layouts should be chosen based upon the following recommendations:
   - Locate micropile walls between 50% and 75% upslope from the slide toe and below sources of external load such as embankments or roadways.
   - Space micropile pairs close enough together to prevent plastic flow of soil between elements while still providing an economic design. This is generally between 0.8 and 1.1 meters (2.5 - 3.5 feet).
   - Start by using upslope batter angles between 25° and 35°. Downslope micropiles should be installed close to vertical or slightly below (5° to 10°).

3. The micropile/cap beam system is treated as a structural frame and the required resistance to provide global stability is applied as a uniformly distributed load acting downslope and parallel to the slide surface. Axial loads transferred to the micropiles should be determined using basic structural analysis software. The micropile wall geometry and distributed load determined in steps 2 and 3 are used along with an equivalent depth of fixity based upon the type of material below the slide plane.

4. Check structural design of micropiles for axial load using the cross sectional properties. Factored tensile and compressive resistances are compared against the factored micropile loads to ensure that LRFD criteria are met.

5. Micropiles are designed geotechnically using presumptive values of allowable bond stress for each layer of the soil/micropile interface. Alternatively, field load tests can be conducted to determine actual bond strengths. Resistance is assumed to come only from side friction and end bearing is neglected. Geotechnical lengths should be adequate to resist the unfactored micropile loads determined in step 4.

After performing the above design steps for four documented case histories and comparing the difference between original and modified designs, several important observations are noted:

- The proposed methodology achieves similar designs to those originally presented for each individual site when using the same parameters. Since these stabilization projects have been successful, it is important that the proposed design method predicts adequate strength within the system to provide global stability.

- The proposed methodology provides a simpler design procedure for basic micropile walls than do the previously presented methods using computer *p-y* analysis, while still achieving reasonable results.

The actual behavior of the soil and micropile interaction is complex and statically indeterminate. By using the proposed procedure, the system becomes statically determinate while using a more realistic model of micropile wall behavior. More accurate loading conditions are also used, resulting in a simplified design that achieves reasonable results. Micropile layouts can be analyzed efficiently to maximize benefit and economy with limited use of computer software. In practice, this allows design engineers to quickly determine if a micropile wall is a feasible option for a particular site.

For large scale projects, a micropile wall may not be the most suitable stabilization option. Based upon analyses presented in more detail by Halvorson (2012), it appears that if a landslide is greater than 10 m deep or if a minimum spacing between individual micropiles of approximately 0.4 m (1.25 ft) cannot be achieved using typical micropile cross sections, a micropile wall alone may not be suitable to provide stabilization. In this case, the addition of ground anchors may be warranted or even the use of a different stabilization technique. If a micropile wall is used for a large landslide, a more rigorous analysis (*i.e.* Finite Element Analysis) should be performed prior to final designs. Also, all of the case studies cited herein used micropiles embedded into very stiff soil or rock. More field case histories are needed to assess whether the same benefits can be achieved using micropiles embedded in soft to medium stiff materials.

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