Design of Micropiles for Slope Stabilization

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Figure 1 Photograph of installation of micropiles for slope stabilization at Littleville, Alabama. (photo courtesy of J. Wolosick).

Introduction

The use of micropiles for stabilization of earth slopes has been proven effective through full-scale field implementation at numerous sites. However, use remains limited compared to many other techniques for reasons that include:

- general lack of understanding on the part of many owners and consultants about how and why the technique works;
- questions regarding assumptions invoked in current design procedures and lack of a widely accepted method for analysis and design of micropile stabilization schemes; and
- perception that use of micropiles is generally cost prohibitive except for extremely challenging conditions where other slope stabilization methods cannot be employed.

These issues are interrelated. Several alternative design and analysis procedures have been proposed. These methods have commonalities, but also distinct differences in terms of the general approach, in how forces attributed to the micropiles are incorporated into analysis, and in terms of assumptions about how resisting forces provided by micropiles are established for input into stability analyses. From the viewpoint of many owners and consultants, the lack of a consensus design approach heightens the general lack of comfort with the technique. These issues lead to the understandable result of designers frequently taking conservative design postures, which leads to costs that may be greater than truly needed. Combined, these issues result in micropiles seldom being considered as a mainstream stabilization technique.

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Despite these challenges, micropiles have been successfully used to stabilize earth slopes (Figure 1). Fortunately, several sites where micropiles have been used for slope stabilization have been instrumented to help develop a better understanding of the technique and how it works. This article summarizes key findings and recommendations from a study conducted to collectively review and evaluate design methods in light of the available performance data. This work was funded by the ADSC Industry Advancement Fund and performed under the direction of the joint ADSC/DFI Micropile Committee. A more detailed report is available through the ADSC Technical Library (Loehr and Brown, 2007).

Summary of Key Findings

Most modern computer programs for slope stability analysis provide means to incorporate resistance due to piles, drilled shafts, micropiles, soil nails, and other similar members into slope stability analysis computations. Common implementations require that users input the location of the member and the magnitude and direction of the resisting force(s) to be used in the computations. Specific details of how such forces are input and, to a lesser extent, how they are incorporated into stability calculations vary from program to program. However, all programs generally adopt the perspective that the input forces are *known values* for the stability computations and, as such, are treated in a manner similar to other applied forces such as surcharge loads.

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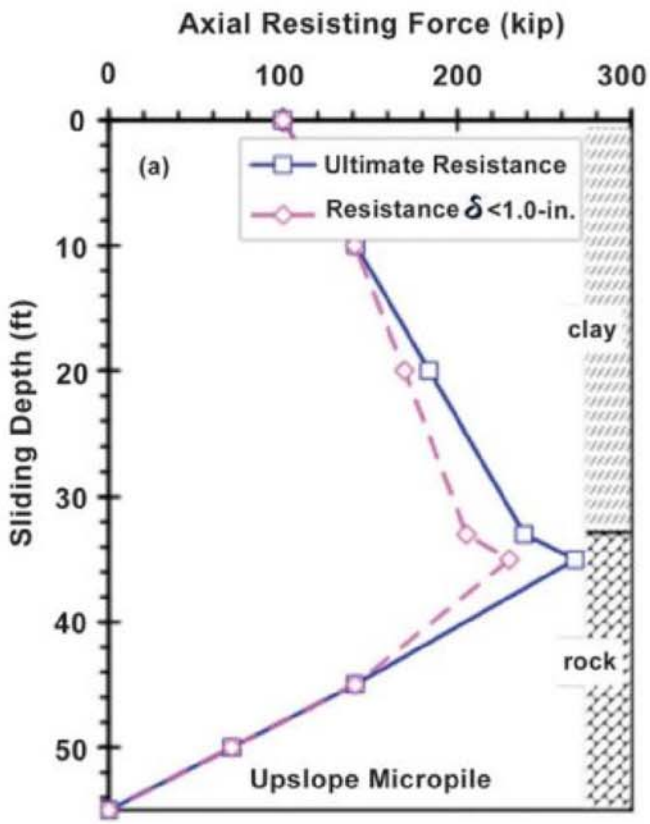

Figure 2 Shows an example of axial resistance function established for micropile in clay socketed into rock.

In general, the resistance provided by micropiles and other forms of reinforcement varies with the location where the sliding surface intersects the micropile. It is therefore necessary to establish "resistance functions" that describe how axial and lateral components of the resisting force vary with location along the micropile (Figures 2 and 3). The principal challenge for design of micropiles for slope stabilization is therefore establishing

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the magnitude of the resistance that will be provided by the micropiles and how this resistance changes with different depths of sliding. Computation of factors of safety for any potential sliding surface is relatively straightforward once these values of micropile resistance are established.

In addition to sliding depth, the resistance that can be mobilized in micropiles used for slope stabilization depends on a large number of factors. The most important of these factors include micropile strength and stiffness, soil strength and stiffness, the magnitude of soil movement, the orientation of the micropiles relative to the direction of soil movement, the presence or absence of a capping beam, and the presence or absence of ground anchors used in combination with the micropiles. The relative proportion of axial and lateral resistance components depends primarily on the position (depth) of the sliding surface and the orientation of the micropile (batter). The controlling failure mode also varies, with soil flow generally controlling for shallow sliding, structural capacity often but not

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always controlling for sliding at intermediate depths, and pullout generally controlling for deeper seated sliding. The complexity of load transfer from soil to micropiles and the large number of potential failure modes necessitates that micropile resistance generally be predicted using soil-structure interaction

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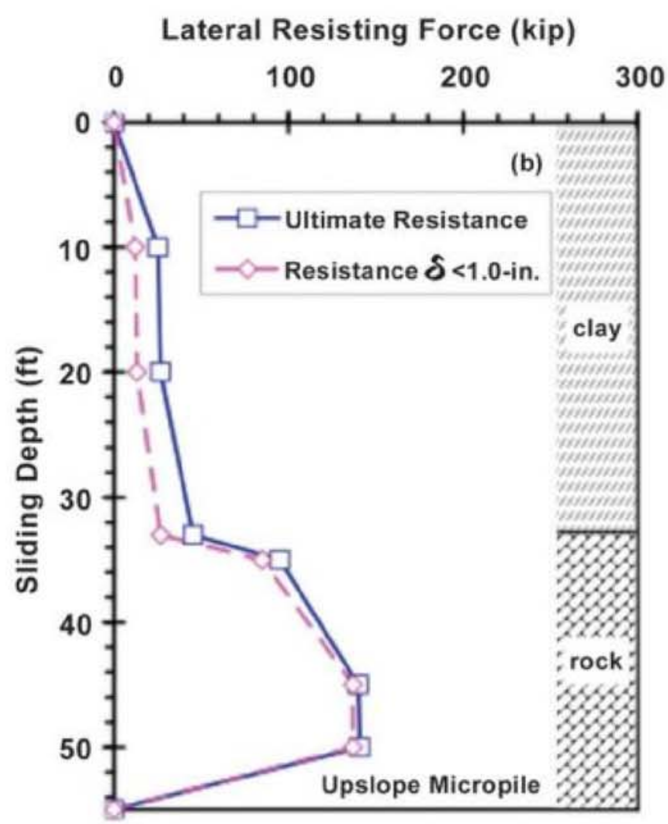

Figure 3 Shows an example of lateral resistance function established for micropile in clay socketed into rock.

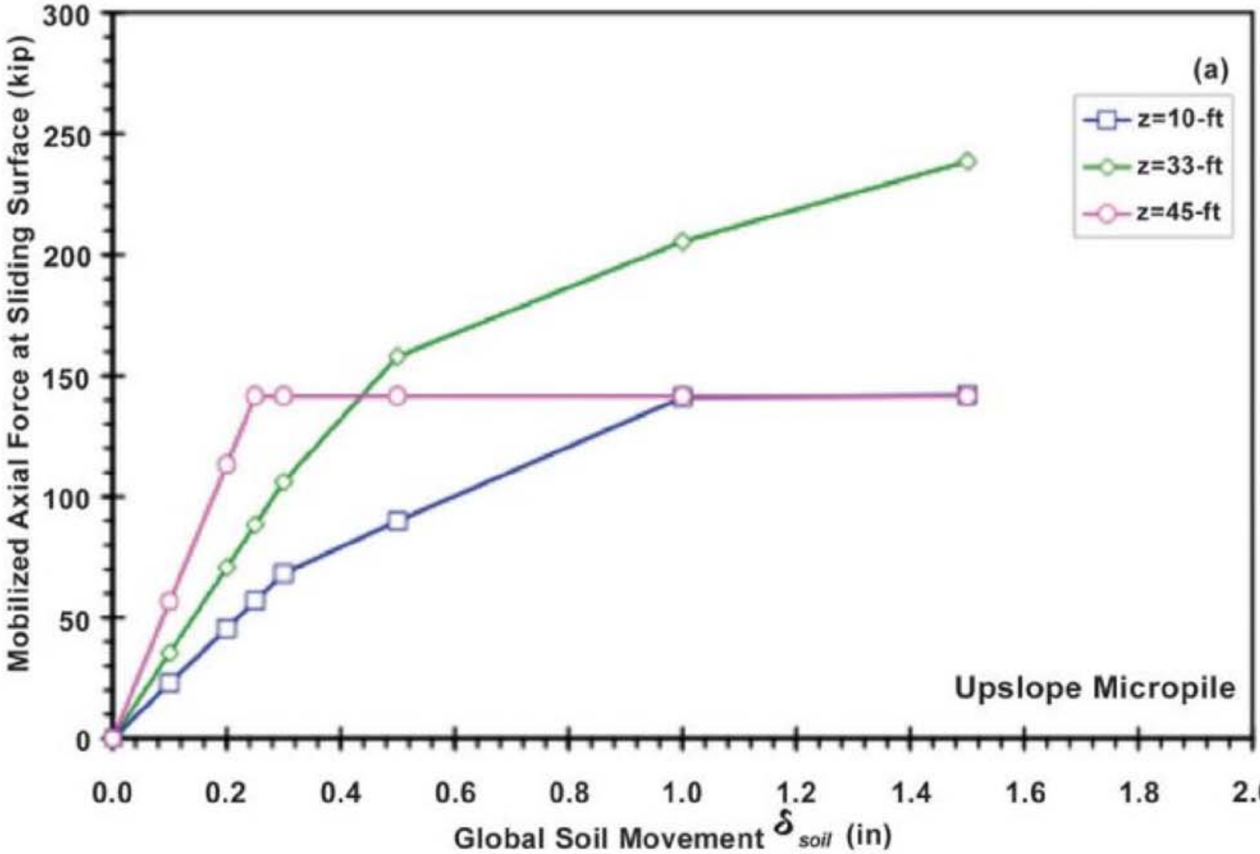

Figure 4 Representative prediction for mobilization of axial resistance in micropile for different sliding depths.

methods (i.e. *t-z* and *p-y* analyses). Use of assumed loading distributions or approximations for micropile resistance leads to erroneous estimates of contributions due to the micropiles, and often to significant errors in estimates of stability. The practice of estimating micropile resistance from the structural shear capacity of the micropiles alone should particularly be avoided, as structural capacity is only one of a number of failure modes that may govern micropile resistance.

Prediction of micropile resistance is further complicated because axial and lateral components of resistance are often mobilized at greatly different rates as shown Figures 4 and 5 (note differences in horizontal scales). The ultimate axial resistance is frequently mobilized at slope deformations of one inch or less. Even in the worst cases evaluated for this project, ultimate axial loads were usually mobilized within two to three inches of deformation. In contrast, substantially greater slope deformations are often required to mobilize significant lateral resistance and the ultimate lateral resistance may not be fully mobilized at movements exceeding a foot or more. Factors such as micropile stiffness and orientation, site stratigraphy, and soil stiffness and strength affect the relative mobilization of axial and lateral resistance. Nevertheless, consideration of the ability to simultaneously mobilize axial and lateral resistance (i.e. compatibility) and to mobilize this resistance within tolerable levels of slope deformation (i.e. serviceability) is necessary when selecting values of resistance to be included in slope stability computations. As an example, Figures 2 and 3 show "compatible" axial and lateral resistance functions established for total slope deformations of 1 inch (dashed lines) as compared to the ultimate axial and lateral resistance (solid lines). At some depths, the "compatible" and ultimate resistances are similar, while at other depths the compatible resistance values are up to 50 percent less than the ultimate values.

Results of back-analyses performed for the instrumented case histories considered in this project suggest that current empirically derived *p-y* and *t-z* models developed for conventional foundation loading are not necessarily appropriate for use where piles are loaded by moving soil. Figures 6 and 7 illustrate the generally favorable comparisons achieved among measured val-

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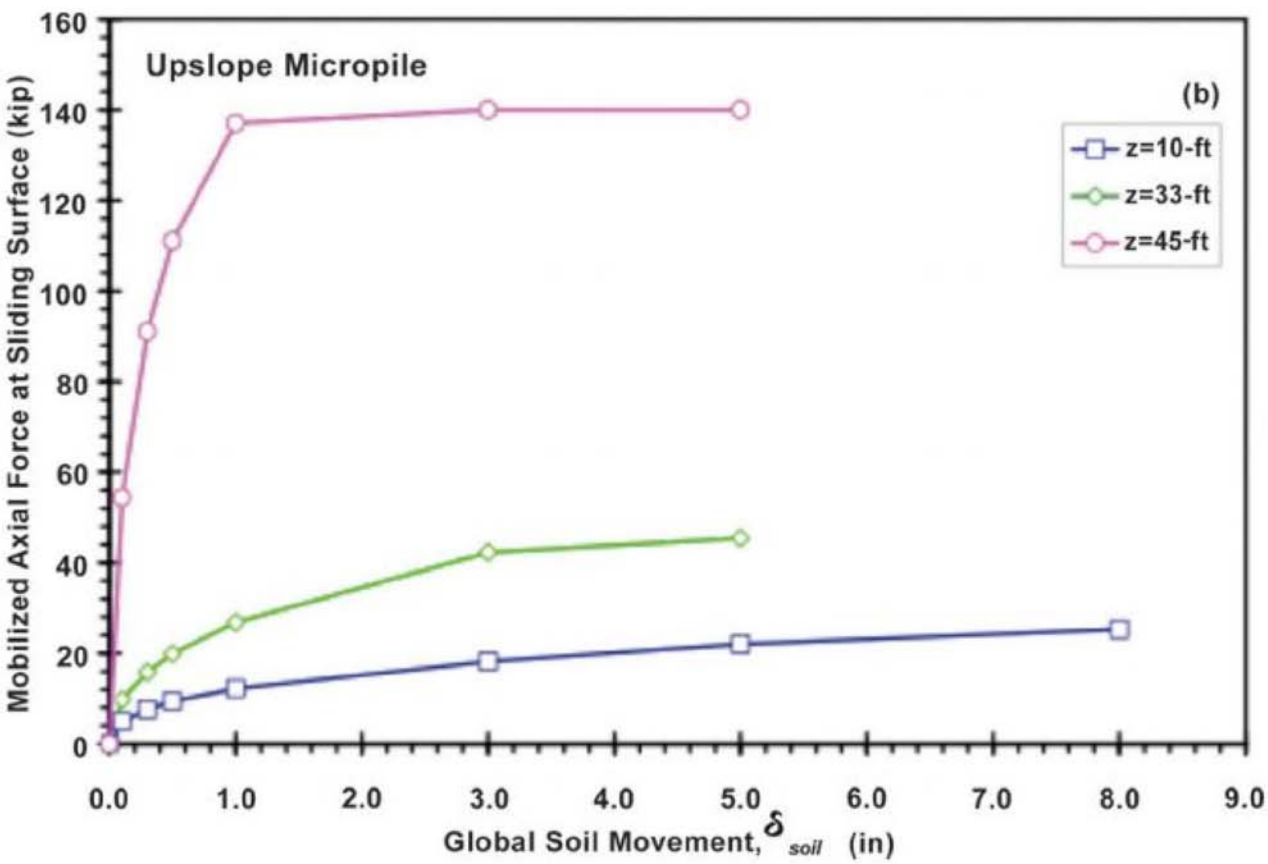

Figure 5. Representative prediction for mobilization of lateral resistance in micropile for different sliding depths.

ues of axial load and bending moment from one of the case histories considered with predictions from *t-z* and *p-y* models established through back-calculations for the case histories. The symbols shown in Figures 6 and 7 indicate measured values derived from strain gage measurements taken from gages placed at two stations (STA 2+70 and STA 1+70), while the solid lines show the predicted distributions of axial load and bending moment along the micropiles. While based on a limited number of case histories, these results of analyses performed for this project suggest that current *p-y* and *t-z* models should be modified to be substantially "softer" (by as much as a factor of five) especially when the slope materials are soft. Results from other research performed by the authors indicate different levels of modification are necessary, but the overall need to consider the form of loading remains.

Micropiles inclined upslope tend to develop tensile axial resistance whereas micropiles inclined downslope tend to develop compressive axial resistance. Both tensile and compressive axial forces in the micropiles generally provide some direct resistance to sliding (i.e. a component acting parallel to the direction of sliding) that acts to improve overall slope stability. However, tensile forces in the micropiles tend to improve stability more than compressive forces because tensile force increases the normal stress on the slide surface, which indirectly increases the overall resistance by increasing soil shear strength under drained loading conditions. Conversely, compressive forces in the micropiles tend to decrease the normal stress on the sliding surface near the micropiles and indirectly to reduce the overall resistance compared to that provided by a micropile placed into tension.

The field measurements evaluated and analyses performed for the project indicate that use of ground anchors tensioned through a capping beam can substantially reduce the potential resistance provided by micropiles inclined upslope if a portion of the anchor load is transferred to the depth of sliding. This effect is particularly pronounced if the soils above the depth of sliding are soft because the anchor load can be easily transferred to the sliding depth.

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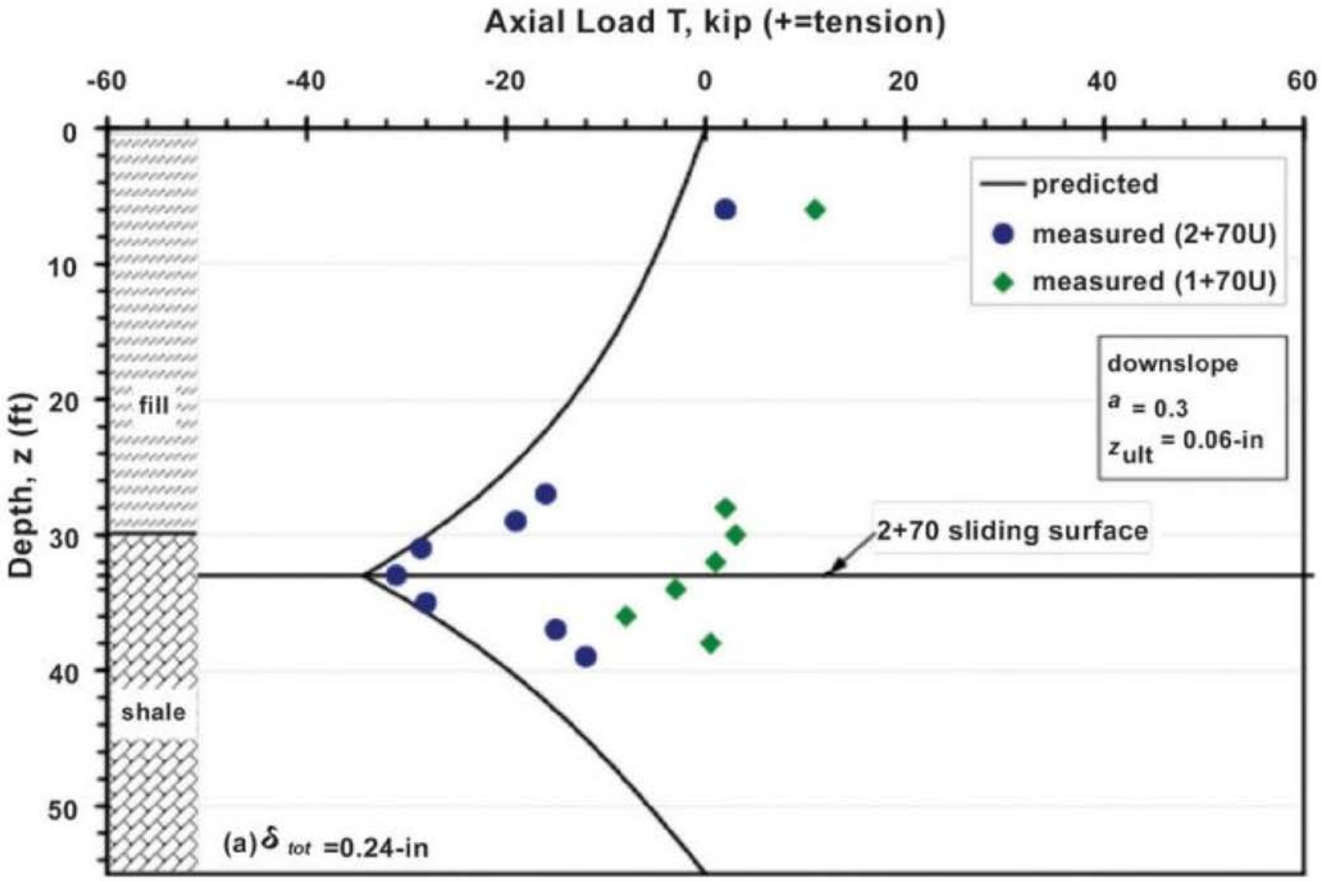

Figure 6 Typical comparison of measured and predicted axial load in micropiles from Littleville, Alabama site.

Finally, the predicted ultimate axial, bending, and shear loads from calibrated models for the cases evaluated were often substantially less than the structural capacity of the micropiles that were actually used, which suggests that the micropiles have substantial excess structural capacity that cannot be mobilized because other failure modes control the ultimate resistance. Realization of this issue in design, and more precise consideration of the anticipated loading to be expected in the micropiles, could lead to substantial cost savings for micropiles in future slope stabilization applications because smaller structural sections can be utilized while maintaining the same resistance to sliding.

Practical Implications

The fact that axial loads are often mobilized at smaller soil movements than lateral loads suggests that axial loads are often the primary contributor to overall slope stability for classical "A-frame" micropile configurations, at least at "working deformations." In a sense, the lateral resistance may be viewed as providing important margins of safety against sliding, but in most cases the axial loads will tend to be the predominant load transfer mechanism under normal working conditions. This is analogous to the contributions of side shear (which frequently dominates load transfer at working loads) and end bearing (which frequently is mobilized at much greater settlements) to the stability of axially loaded deep foundations.

The importance of axial loads to some extent conflicts with assumptions inherent in many current design procedures, which are largely based on consideration of lateral resistance. Incorporation of appropriate axial resistance into many commercially available slope stability programs is generally straightforward, but attention must be given to the estimates of axial resistance used and in how they are incorporated into stability analyses. One specific practice that warrants careful consideration is that of including only the component of axial load that acts parallel to the sliding surface and ignoring the effect of the component acting perpendicular to the sliding surface. Because the perpendicular component changes the normal stress on the sliding surface, this practice can lead to unconservative results in some cases or over conservative results in others depending on the specific problem. The importance of axial loads also places increased importance on accurate estimation of shear strength parameters on the sliding surface(s) since errors in soil shear strength parameters can lead to over-or under-estimation of the benefits of the micropiles.

Use of ground anchors that may reduce tensile loads or even

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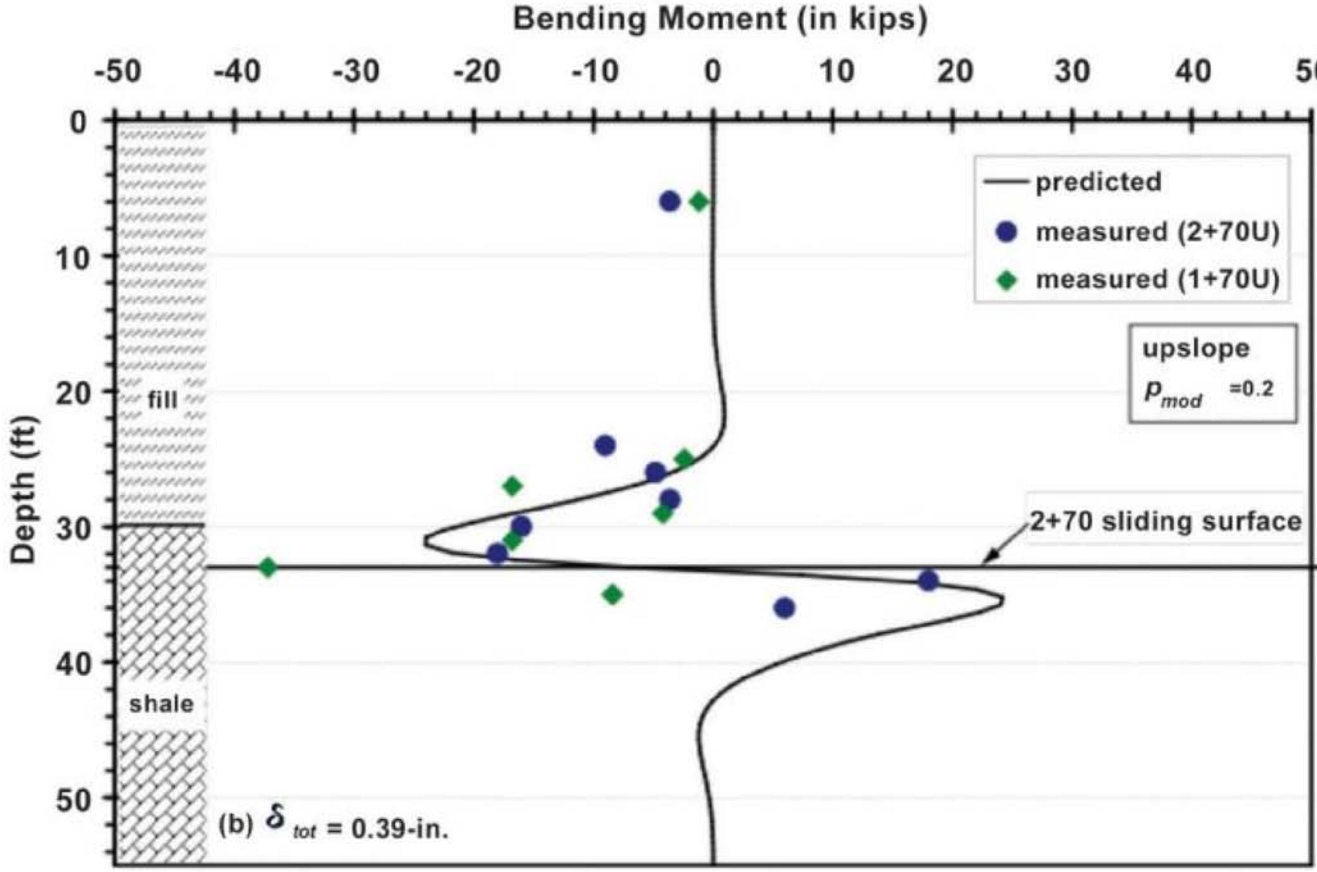

Figure 7 Typical comparison of measured and predicted bending moment in micropiles from Littleville, Alabama site.

induce compressive loads in the micropiles should be carefully considered as they can diminish the potential benefits of the micropiles. There are instances where the beneficial effects of anchors outweigh compromising some of the beneficial effect of the micropiles, such as when micropiles are necessary to create a reaction for the anchors or where sufficient stabilization cannot be achieved with micropiles alone. In such cases, micropiles will still provide some beneficial shear resistance but steps should be taken to limit the impact of the anchors on the micropiles to the extent possible.

Recommended Approach for Predicting Micropile Resistance

The project report (Loehr and Brown, 2007) describes a recommended approach for predicting micropile resistance for slope stabilization applications. The key features of the approach are that it accounts for compatibility between mobilization of axial and transverse (shear) components of micropile resistance, which are known to mobilize at substantially different rates, while also accounting for the effects of pile and soil stiffness and pile batter.

The analyses to predict micropile resistance are performed by independently considering the axial and transverse (shear) load transfer in an uncoupled manner. The general approach is to first resolve the global soil movement into components perpendicular and parallel to the micropile. The axial and transverse components of soil movement are then used as inputs to independently assess the mobilized axial and lateral resistance for a specific overall soil movement using *t-z* and *p-y* analyses, respectively, as suggested by Isenhower (1999). These computations are repeated for several values of soil movement to develop results showing how the axial loads, bending moments, and shear forces are developed with overall slope movement. These computations are then repeated for different potential sliding depths to establish design values for the axial and lateral resistance functions based on tolerable deformation limits established for a particular case.

The approach is demonstrated in the project report (Loehr and Brown, 2007) through a simple, but realistic example using "hand calculations." The report also describes application of the approach for more complex cases without restrictions or simplifying assumptions regarding stratigraphy, slope geometry, or micropile characteristics, and including consideration of the non-linear nature of the micropile response. The greatest limi-

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tation of the recommended method is that it is an "uncoupled" method meaning that interaction between micropiles connected via a capping beam is not accurately reflected. However, results obtained for analyses performed for several case histories and hypothetical cases suggests that this limitation has little practical effect as long as the potential sliding surface is relatively deep compared to the dimensions of the capping beam.

Recommendations

The proposed method is generally suitable for predicting the mobilization of axial loads and bending moments (or shear resistance) in micropiles used for slope stabilization with reasonable accuracy. The method is general enough to permit modeling of cases with complex slope geometries and varying micropile characteristics (e.g. capacity, inclination, stiffness, etc.) without undue approximations and simplifications. The uncoupled axial and lateral analyses utilized in the method appear to work well in cases where sliding is relatively deep, which limits the influence of the capping beam and ground anchors that are frequently used in combination with micropiles. In cases where sliding is more shallow, the proposed uncoupled analyses may not accurately predict the mobilization of micropile resistance if a capping beam is utilized, especially if used in conjunction with ground anchors placed through the capping beam.

While the proposed method is capable of accurately predicting micropile resistance in slope stabilization applications, substantial modifications to current empirically established *p-y* and *t-z* models may be required. Specifically, current *p-y* and *t-z* models must be modified to produce a "softer" response to match observations from full-scale field performance. Based on analysis of the case histories considered for this project, use of conventional models will tend to overpredict the resistance that can be mobilized at a given soil movement. The appropriate magnitude of *p-y* and *t-z* reductions is still a matter of debate, but analyses performed for instrumented case histories for this project suggest that it could be as great as a factor of five.

Because the ultimate axial resistance is generally mobilized at total soil movements of a few inches or less, the axial resistance of micropiles can often be reasonably estimated using simple limit state approaches (i.e. without soil-structure interaction analyses). Notable exceptions to this statement include instances: (1) where micropiles are nearly perpendicular to the sliding surface, in which case the axial component of soil deformation is very small and, thus, large overall soil movements may be required to mobilize substantial axial resistance; (2) where micropiles have characteristics that significantly differ from those commonly employed; or (3) where there is potential for anchor loads to be transferred to the depth of sliding.

In contrast, the lateral or shear resistance of the micropiles should be estimated using *p-y* analyses in all cases to predict mobilization of shear resistance as a function of total soil movement. For these analyses, due consideration should be given to the magnitude of deformations that can be tolerated for a particular case. The practice of computing the shear resistance for micropiles based on the ultimate bending (moment) capacity of the micropile sections should be avoided because soil movements required to mobilize such resistance is generally larger than can be practically tolerated in many cases and other failure modes may control the maximum shear resistance.

The practice of considering only the component of micropile resistance acting parallel to the sliding surface should also be avoided because the component acting normal to the sliding surface can also have a substantial effect on stability. This effect can be either positive or negative depending on the specific conditions present.

The importance of axial loading should also focus attention on estimates for the ultimate side shear capacity of the micropile-soil (and potentially the grout-steel) interfaces for micropiles. This may be accomplished by acquiring quality measurements of shear strength parameters along the length of the piles, through field load testing, or some combination of both methods for establishing realistic side shear capacities for the micropiles. If field load tests are performed, consideration must be given to the drainage conditions in the soil since common field load tests are performed under conditions that are predominantly undrained, while actual field loading in slopes is more likely to be partially or fully drained.

Finally, ground anchors anchored through a micropile capping beam should be used with some caution since the anchor forces may compromise the beneficial effects of the micropiles on stability. Ground anchors may still be justified on the basis of overall stability, but it is important that possible detrimental effects on upslope micropiles be properly considered in evaluating overall stability.

References

Loehr, J.E., and D.A. Brown (2007), *A Method for Predicting Mobilization of Resistance for Micropiles Used in Slope Stabilization Applications*, Report submitted to the joint ADSC/DFI Micropile Committee, 57p.

Isenhower, W.M. (1999), "Analysis of Pile Groups Subjected to Deep-seated Soil Displacements," *Analysis, Design, Construction, and Testing of Deep Foundations, Proceedings of the OTRC '99 Conference*, ASCE, GSP No. 88, pp. 150-164.

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