FRICION LOSS IN TIEBACK ANCHORS USED FOR LANDSLIDE STABILIZATION

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Introduction

Steel-strand tieback anchors have been used by the geotechnical community to support shoring systems for many decades, and more recently as a means to stabilize landslides. For strand encased in grease-filled plastic sheathing, which is intended to allow the strand to elongate freely, some load can still be transferred by friction between the strand and the grease and between the grease and sheathing. The sheathing then transfers load to the surrounding grout and, in the case of ground anchors, to the surrounding soil or rock. The resulting decrease in load over the length of the unbonded zone is known as “friction loss.”

A widely used criterion for ground anchor acceptance based on load testing is that the measured anchor elongation must achieve a minimum value of 80 percent of the theoretical elastic elongation, or in other words the actual elongation can be up to 20 percent less than the theoretical value. This ensures that the majority of the load applied at the anchor head is reaching the bond zone behind the assumed failure surface, since load shed within the failure mass does not contribute to stability. This criterion acknowledges that friction loss is an inherent feature of the anchor system which cannot be eliminated completely, only minimized.

For shoring projects, the governing performance criteria is usually that the wall horizontal deflection must not exceed some threshold value, and the 80-percent criterion was developed as a “rule of thumb” that was found to satisfy this performance goal for most anchored shoring systems. In most applications, a properly manufactured and properly installed ground anchor will easily meet the 80-percent elongation criterion. However, there have been several cases in recent years in which anchors being used for landslide stabilization and having unbonded lengths in the range of 80 to more than 200 feet have shown an unusually high failing rate with respect to the 80-percent criterion. This raises the question of whether the 80-percent criterion is applicable to all ground anchors or if it should be limited to anchors within a certain range of unbonded length. In particular, the question is whether friction loss increases with unbonded length to a point at which the anchor elongation can be expected to fall below 80 percent of theoretical elongation.
even if good construction practices are followed. If that is the case, acceptance criteria for anchors with long unbonded lengths, such as are now being used in landslide stabilization applications, may require modification from the 80-percent criterion.

In this study, tieback load test data from a variety of shoring and landslide-stabilization projects are analyzed to assess the influence of various parameters on friction loss. A case study is presented in which engineering controls are implemented to directly measure friction loss. The importance of considering friction loss in slope stability calculations is also examined.

**Analysis of Friction Loss**

The following relationship is often cited (e.g., PTI, 2006) as an approximation of load \( P(x) \) as a function of distance \( x \) from the anchor head:

\[
P(x) = P_0 e^{-(a\mu + Kx)}
\]

(1)

Where \( P(x) \) is the load in anchor at distance \( x \) from the anchor head, \( P_0 \) is the load at the anchor head (at \( x = 0 \)), \( a \) is the cumulative change in angle of the strands (radians) from the stressing point to distance \( x \), \( \mu \) is the coefficient of angular friction, \( K \) is the wobble coefficient of friction (radians per unit of length), and \( x \) is the distance from the stressing point.

The first term in the exponent, \( a\mu \), represents the effect of cumulative change in angle over the length of the strand and is useful for calculating friction loss in precast-prestressing applications where the strand is supported at known locations in the structure (e.g., the strand is draped over supports in the concrete form). For such applications in which the angular change is intentional, \( a\mu \) can easily be evaluated incrementally over each support interval. For ground anchors the strand is intended to be perfectly straight and this term is not applicable. Equation 1 reduces to:

\[
P(x) = P_0 e^{-Kx}
\]

(2)

Unintentional curvature of the strand is expressed in terms of the “wobble coefficient,” \( K \), which is the product of angle change per unit of length (e.g., radians/ft) and the coefficient of angular friction (unitless) between the sheathed strand and grease. The normalized load at a distance \( x \) from the anchor head is given by:

\[
\frac{P(x)}{P_0} = e^{-Kx}
\]

(3)

Under a tension load, the theoretical elastic elongation assuming no friction loss is evaluated according to Hooke’s Law as:

\[
\Delta_{elastic} = \frac{P_0 L_u}{AE}
\]

(4)

Since \( P \) varies over the unbonded length \( L_u \) due to friction loss, anchor elongation must be expressed in its integral form:

\[
\Delta = \frac{P_0}{AE} \int_0^{L_u} e^{-Kx} dx
\]

(5)

Solving the integral, the expected elongation with friction loss taken into account is given by:

\[
\Delta_{friction} = \frac{P_0}{AE} \left[ -e^{-Kx} \right]_0^{L_u} = \frac{P_0 L_u}{AE} \left( 1 - e^{-Kx} \right)
\]

(6)

The “normalized elongation,” or ratio of elongation with friction loss taken into account (Equation 6) to the theoretical elastic elongation without friction loss (Equation 4), can be expressed by:

\[
\frac{\Delta_{friction}}{\Delta_{elastic}} = \frac{\frac{P_0}{AE} \left[ -e^{-Kx} \right]_0^{L_u}}{\frac{P_0 L_u}{AE}} = \frac{1 - e^{-Kx}}{1 - e^{-Kx}}
\]

(7)

Or expressed as percent elongation (EL):

\[
EL = 100% \times \left[ 1 - e^{-Kx} \right]
\]

(8)

Equation 8 provides a tool to evaluate the expected elongation, with friction taken into account, as a percentage of theoretical elastic elongation. The criterion for ground anchors under proof or performance load testing in the field is usually that \( EL \geq 80\% \) based on the recommendations of the Post-Tensioning Institute (2004).

In Figure 1, the percent elongation as calculated by Equation 8 is plotted as a function of anchor free-stressing length. (For the remainder of this paper, unbonded length is assumed to include the jack length during testing, i.e. free stressing length is equal to unbonded length). Three curves are shown, each representing a different value of \( K \) ranging from 0.001 to 0.005 radians per foot. The 80-percent criterion is shown for
reference as the blue dashed line. Note that even for small values of $K$, indicating a very straight hole and low friction loss, there is some maximum length beyond which the 80-percent criterion cannot possibly be satisfied.

![Figure 1: Effect of wobble coefficient, $K$, on the percentage elongation achieved during load testing for a range of unbonded lengths.](image)

Theoretically, $K$ is a function of two physical interactions: (1) friction between the grease and the steel strand, and between the grease and the sheathing, which are material properties, and (2) the amount of curvature along the length of the strand. Because of the inherent variability of ground anchor systems, a theoretical or experimental evaluation of these interactions aimed at establishing numerical values of $K$ is not likely to produce a practical result. An empirical approach that could provide useful insight is to establish back-calculated values of $K$ from a database of field load tests on ground anchors. $K$ can be back-calculated from a proof or performance load test using Equation 8 if the unbonded length and percent elongation are known from the test. Because $K$ appears in the exponential term in the numerator and also in the denominator, there is not a closed-form analytical solution to Equation 8, and $K$ must therefore be established through an iterative solution approach. The authors have developed a spreadsheet for this purpose that determines $K$ for a given set of results from an anchor load test.

The objective is to back-calculate $K$ from field load test data to establish (1) a range of “typical” wobble coefficients for routine projects and (2) the influence of various parameters on the wobble coefficient, such as anchor inclination, anchor manufacturer, soil/rock conditions, etc. The authors have compiled a database of tieback anchor load tests used for shoring and landslide stabilization projects and back-calculated wobble coefficients for each test, which are summarized in Table 1. The full database of tests and calculations will be included in a forthcoming report to be published.

Table 1: Summary of tieback anchor load test database

<table>
<thead>
<tr>
<th>Project #</th>
<th>Name</th>
<th># Tests</th>
<th>Avg. Free Stressing Length (ft)</th>
<th>Avg. Elongation</th>
<th>Min/Max</th>
<th>Avg.</th>
<th>COV K (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$K$ (rad./ft)</td>
<td>$K$ (rad./ft)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Togwotee Pass</td>
<td>20</td>
<td>149</td>
<td>83%</td>
<td>0.0005/0.0040</td>
<td>0.0026</td>
<td>39</td>
</tr>
<tr>
<td>2</td>
<td>Cuesta Grade</td>
<td>108</td>
<td>129</td>
<td>79%</td>
<td>0.0005/0.0111</td>
<td>0.0038</td>
<td>43</td>
</tr>
<tr>
<td>3</td>
<td>Anonymous</td>
<td>6</td>
<td>128</td>
<td>91%</td>
<td>0.0011/0.0022</td>
<td>0.0016</td>
<td>26</td>
</tr>
<tr>
<td>4</td>
<td>Anonymous</td>
<td>2</td>
<td>115</td>
<td>94%</td>
<td>0.0006/0.0013</td>
<td>0.0009</td>
<td>53</td>
</tr>
<tr>
<td>5</td>
<td>Anonymous</td>
<td>35</td>
<td>108</td>
<td>85%</td>
<td>0.0009/0.0057</td>
<td>0.003</td>
<td>34</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>171</strong></td>
<td><strong>127</strong></td>
<td><strong>82%</strong></td>
<td><strong>0.0005/0.0111</strong></td>
<td><strong>0.00294</strong></td>
<td><strong>46</strong></td>
</tr>
</tbody>
</table>
by the DFI Tiebacks and Soil Nailing Committee.

**Results**

Back-calculated values of $K$ from the project database are presented in Table 1 and plotted versus unbonded length in Figure 2. The linear best-fit line shows a general trend of increasing wobble coefficient with increasing unbonded length. That is to say that the longer anchors in our database were more likely to have greater total friction loss, but also greater friction loss per unit length over the unbonded zone. We hypothesize that the primary factor influencing this trend is that the drill stem becomes more flexible as it is advanced further into the ground, making it more prone to deviating from a straight course when an irregularity is encountered. The chance that such an irregularity will be encountered are inherently greater in certain ground conditions, such as boulders in a soil matrix, bedding planes or foliation that are sub-parallel to the drilling direction, contacts between fill and native soil or rock, or any subsurface feature that leads to borehole deviation and therefore greater curvature over the anchor unbonded length.

The large scatter in the data set plotted in Figure 2 does not allow us to develop a meaningful relationship between friction loss and unbonded length, which is not surprising given the inherent variability of the subsurface. In other words, the equation for the best fit line would be of little practical significance. Note that several anchors with unbonded lengths between 100 and 200 feet did satisfy the 80-percent criterion. Furthermore, the limited size of the database does not allow us to quantify the relative influence of parameters such as anchor inclination or ground conditions with statistical significance. Nonetheless, designers and contractors should keep in mind that several parameters are likely to influence the wobble coefficient even if our results cannot quantify the corresponding amount of friction loss.

**Figure 2: Wobble coefficient versus unbonded length data.** For a given unbonded length, the dashed line shows the maximum wobble coefficient for which achieving elongation of 80% of the theoretical elastic elongation is possible. Data points plotting above this line failed the 80% criterion.
For example, placing the anchor in a relatively long hole that is inclined at a shallow angle will be difficult. Anecdotal reports from the Togwotee Pass and Cuesta Grade landslide stabilization projects indicated that under such conditions, the contractor resorted to forcing the anchor into the hole by “brute force.” This procedure is likely to induce curvature in the anchor that becomes permanent when the anchor is grouted, leading to greater friction loss. A potential solution to this problem is two-stage grouting in which the bond zone is grouted and a small alignment load is applied to straighten the unbonded zone before it is grouted. Although simple in concept, however, this procedure is time-consuming and difficult to perform, and hence not often utilized in the USA. Two-stage grouting is purportedly more common in Europe.

Implications for Slope Stability Analysis

Limit-equilibrium slope stability analysis is often conducted to estimate the factor of safety of a landslide or potentially unstable slope and to assess the increased factor of safety that would be obtained by installing tieback anchors. In such analyses, the engineer specifies a design load in each anchor, and the computer program determines the corresponding resisting force at the point of intersection of the anchor with the failure plane and the increased normal stress acting on the soil or rock at this point. The magnitude of the load in the tieback anchor has a direct impact on the factor of safety computed by the program.

When these anchors are constructed in the field, if the average friction loss over the unbonded zone is 20 percent of the design load, this means that only 80 percent of the load that was assumed to reach behind the failure plane in the analysis is actually doing so, and according to typical project specifications this is acceptable. What is often ignored in practice is that the factor of safety computed during the slope stability analysis is not actually being achieved in the field when this is the case. Project owners are likely unaware that the geotechnical report specifies a factor of safety for the slope, while the specifications effectively allow the project to be constructed with a lower factor of safety. To determine the actual factor of safety, the engineer would need to re-run the slope stability analysis using the actual load in the anchor determined by load testing.

A more practical approach would be to specify a design load that achieves the target factor of safety with friction loss over the unbonded zone explicitly considered. For example, if a 100 kip anchor load is needed to achieve the target factor of safety, the engineer should specify a design load for construction of 100 kips/0.8 = 125 kips. There is no rational basis for specifying a target factor of safety and then not enforcing construction specifications that achieve this factor of safety in the real system.

Minimizing Friction Loss: A Case Study

For critical life safety projects or routine projects for which the designer feels that the ground conditions or other factors may lead to unacceptably large friction loss, engineering controls can be implemented to reduce the uncertainty with regards to the wobble coefficient. An example is described here.

As part of a recent slope stabilization project for an adversely-dipping, weak sedimentary rock slope in Southern California, two tieback anchors with unbonded lengths of 130 feet were performance tested to 133 percent of design load (pictured in Figure 3). Each anchor was instrumented with DYNA Force® elasto-magnetic sensors, manufactured by DYWIDAG-Systems International, mounted directly to the strands over the unbonded and bonded zones to measure the load-transfer between the strands and the ground and to determine where along the length of the anchor the load transfer was occurring. Furthermore, the equipment used to drill the anchor holes was equipped with a gyroscopic device that measures the deviation of the drill string from perfectly straight, and anecdotal reports indicated that the device measured less than one-percent deviation along the length of the drilled holes. The anchors were inclined at 45 degrees in order to intersect the potential failure plane, which was assumed to be inclined at a relatively shallow angle of about five to ten degrees. A crane-supported dolly was used to mechanically feed the anchors into the drilled holes, and the contractor did not report any difficulty or blockages during the placement.

Given the reported ease of installation and “straightness” of the drilled holes along with the relatively steep anchor inclination, it is expected that the 80-percent criterion would be easily satisfied for these anchors, and the instrumentation verified that this was the case.
Figure 3: Installation and load testing of tieback anchors for mitigation of a recent landslide in Southern California. Photographs by B. Turner 2011—2014.
Figure 4 shows normalized load transfer curves for the two test anchors. The behavior illustrated by these anchors is a textbook example of minimal load transfer over the unbonded length and rapid load transfer in the bond zone in rock. The two test anchors achieved 93 and 98 percent of theoretical elongation over their unbonded lengths based on the dial-gage readings taken at the ground surface. The DYNA Force® sensors showed that the friction loss that did occur was uniformly distributed over the unbonded zone of the anchor, suggesting that the loss was due to minor yet unavoidable load transfer through the strand-grease-sheathing-grout interface as opposed to wobble concentrated in a single zone.

This project provides a good example of how advanced instrumentation can be used to directly measure friction loss over the unbonded zone of a tieback anchor, reducing uncertainty with regards to the amount of stabilizing force that is reaching the material behind the potential failure plane. In addition, the load transfer in the bond zone is directly measured, allowing the designer to verify the ultimate bond stress used for design and providing a chance to optimize the lengths of the remaining anchors. Because measured friction loss was relatively low for this project, the performance test results do not shed much light on the factors that contribute to wobble, other than to suggest that hole-straightness and relatively steep hole inclination are conducive to reducing wobble as hypothesized.

Conclusions

For this study, we reviewed data from several projects in which tieback anchors were used for either landslide stabilization or shoring. We used the "wobble coefficient" as a proxy to relate the amount of unintentional deviation from straightness in the anchor to the amount of friction loss over the unbonded length.

The data we collected show a general trend of increasing wobble coefficient with increasing unbonded length, meaning that longer anchors are more likely to fail the 80-percent minimum elongation criterion. While we hypothesize that shallow anchor inclination and certain geologic conditions may lead to higher wobble, the amount of scatter in our dataset does not allow us to draw specific conclusions about these effects. Nonetheless, designers and contractors should be aware that the probability of not meeting the 80-percent minimum elongation criteria goes up with increasing anchor unbonded length.

Regardless of whether anchors pass or fail the 80-percent criterion, slope stability analyses that include the resisting force of the anchor should only consider the magnitude of load that is expected and specified to reach the bond zone. If the designer requires more resisting force to reach a target factor of safety, larger anchors or a higher minimum elongation criteria must be specified. Likewise, anchors that fail the 80-percent criterion do not necessarily have to be rejected outright if additional slope stability analysis considering the actual magnitude of load reaching the bond zone can be shown to still satisfy the target factor of safety when supplemental anchors are added. This recommendation is consistent with the PTI specifications (2004) although it is not typically included in project specifications.
Methods for directly measuring load transfer between the anchor and the ground are available, such as strain gages or direct-force measuring devices that can be mounted to the anchor strands along its length. Incorporating these measurements into the performance test(s) for critical projects or projects with a large number of anchors can (1) reduce uncertainty about where friction loss is occurring, which provides an opportunity to address the problem if excessive loss is occurring in a particular zone, and (2) allows for a direct measurement of the load transfer in the bond zone, which can be used to optimize the lengths of the remaining anchors.

Since many anchors from our database with unbonded lengths in the range of 100 to 200 feet satisfied the 80-percent criterion, we do not recommend a modified minimum elongation acceptance criterion for long anchors at this time. More data will potentially allow us to draw quantitative conclusions about the influence of specific parameters such as anchor hole inclination and the manufacturing processes used by various anchor manufacturers. The authors would be very grateful if practitioners with access to performance load test data that meet the needs of this project would submit the data for inclusion in the project database. All data can be kept anonymous if necessary.

Acknowledgments

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