Tipping the Balance

By Daryl Wurster, PE

Wurster Engineering & Construction, Inc.
Lake Keowee is located in the Upstate of South Carolina and was created for power production and for recreation.
The Oconee Nuclear plant is located on Lake Keowee and as a result, water levels are held fairly constant. Much of the waterfront has residential development. Lakefront property in the lower portions of the lake is gently to moderately sloping.

The lake is about 26 miles long with about 300 miles of shoreline.

Several slow moving landslides have been observed, affecting some of the residential developments.

Movements so far appear to be isolated to residential properties. However, this movement could also effect transportation and hydropower infrastructure.

This pattern of movement appears to be unique to the Keowee area, as such movements have not been widely observed on the adjacent lakes.

The ground movement is typically very slow moving and deep seated, often encompassing several acres of ground.

Uniquely, the surface profile of the moving areas is often rather flat, ranging from 3H:1V to 7H:1V, and the slides typically exit well below the lake surface.
Several known slides in same general area of Lake Keowee with similar characteristics
Three known slides in same general area of Lake Keowee with similar characteristics

- Slope of ground is flatter than might be expected for a slide to occur in this general area. Site grades are typically 3H:1V or flatter
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- Areas with borings and slope inclinometers indicate movement near the soft soil/weathered rock interface
Three known slides in same general area of Lake Keowee with similar characteristics

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- Areas with borings and slope inclinometers indicate movement near the soft soil/weathered rock interface.
- Failure plane is about 30 to 60 ft deep near the shoreline extending out into Lake Keowee.
Three known slides in same general area of Lake Keowee with similar characteristics

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- Areas with borings and slope inclinometers indicate movement near the soft soil/weathered rock interface.
- Failure plane is about 30 to 60 ft deep near the shoreline extending out into Lake Keowee.
- Two of the sites experienced ruptured water lines. We are not sure if the ground movement caused the water lines to break or if broken water lines broke on their own and induced ground movement.
Where are these slides located
REPAIRED SITE
The site was repaired by WEC using battered micropiles with a concrete cap beam and tieback anchors.
REPAIRED SITE

• Site repaired by WEC using battered micropiles with a concrete cap beam and tieback anchors.
• Site is being monitored with slope inclinometers.
REPAIRED SITE

• Site 3 slide was repaired by WEC using battered micropiles with a concrete cap beam and tieback anchors.
• Site is being monitored with slope inclinometers.
• Staged approach was used.
REPAIRED SITE

- Site was repaired by WEC using battered micropiles with a concrete cap beam and tieback anchors.
- Site is being monitored with slope inclinometers.
- Phased approach was used.
- Slide was deep seated and extended into lake.
REPAIRED SITE

- Site was repaired by WEC using battered micropiles with a concrete cap beam and tieback anchors.
- Site is being monitored with slope inclinometers.
- If movement continues, patterned ground anchors will additionally be installed.
- Slide was deep seated and extended into lake.
- Ground movement showed up as separation cracks in house.
REPAIRED SITE

- Site was repaired by WEC using battered micropiles with a concrete cap beam and tieback anchors.
- Site is being monitored with slope inclinometers.
- Phased approach was used.
- Slide was deep seated and extended into lake.
- Ground movement showed up as separation cracks in house.
- Ground was gently sloping.
LAKE KEOWEE
PROPERTY LINE FOLLOWS 804 MSL CONTOUR.
<table>
<thead>
<tr>
<th>Elevation</th>
<th>Description of Materials (Classification)</th>
<th>* Sample Blows</th>
<th>Sample Depth (ft)</th>
<th>N-Value (blows/ft)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td>FILL - Soft to firm, moist, dark red clayey SILT (MH) with little sand</td>
<td>1-2-3</td>
<td>1.5</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>7.0</td>
<td>APPARENT RESIDUAL - Firm, moist, dark reddish brown clayey SILT (MH)</td>
<td>3-3-3</td>
<td>3.0</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>16.0</td>
<td>FIRM, moist to wet, reddish brown to light tan sandy SILT (ML)</td>
<td>3-3-3</td>
<td>6.0</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Loose to medium dense, moist, dark brown and red silty fine to medium SAND (SM) with trace mica flakes</td>
<td>2-3-3</td>
<td>8.5</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>32.0</td>
<td>MEDIUM CLAY, moist white, tan, orange and gray silty fine to medium SAND (SM) with mica</td>
<td>2-2-3</td>
<td>10.0</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>38.5</td>
<td>MEDIUM CLAY, moist white, tan, orange and gray silty fine to medium SAND (SM) with mica</td>
<td>6-6-9</td>
<td>18.5</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>35.5</td>
<td>MEDIUM CLAY, moist white, tan, orange and gray silty fine to medium SAND (SM) with mica</td>
<td>8-9-10</td>
<td>20.0</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>38.5</td>
<td>SOFT WEATHERED ROCK - Sampled as white, tan, orange and gray silty fine to medium SAND (SM)</td>
<td>50/4'</td>
<td>13</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>35.5</td>
<td>Auger refusal encountered at approximately 41 feet below the existing site grades</td>
<td>50/2.5'</td>
<td>100+</td>
<td>19</td>
<td></td>
</tr>
</tbody>
</table>

*Number of blows required for a 140 lb hammer dropping 30" to drive 2" D.D., L.V. T.D. sampler to a total of 18 inches in three 6" increments. The sum of the second and third increments of penetration is termed the standard penetration resistance, N-Value.
Keranen Residence, Inclinometer K-5

Roger Keranen

Sets marked * include zero shift and/or rotation corrections.

C:\TEMP\WRTUA-11PROGRA-15\TILT\K6SEP\GTL
\[ W_x = W \sin \beta = 248.6 \sin 18.9^\circ \]
\[ W_x = 78.5 \text{ kN} \]

\[ F = F = N \tan \phi' = 235.5 \text{ kN} \tan 22^\circ \]
\[ F = 95.3 \text{ kN} \]

FS WITH HOUSE LOAD

\[ FS = \frac{\sum F_x \text{ Resisting}}{\sum F_x \text{ Driving}} = \frac{40.9 \text{ kN} + 95.3 \text{ kN}}{78.5 \text{ kN} + 56.4 \text{ kN}} = 1.36.2 \]
\[ FS = 1.00 \]

FS WITHOUT HOUSE LOAD

\[ FS = \frac{P_{ax} + F}{W_x + P_a} = \frac{136.2}{78.5 + 56.4} = 124.1 \]
\[ FS = 1.09 \]

The results of the block analyses support that the existing factor-of-safety is near 1 assuming that the friction angle along the slide interface is 22 degrees.
Analytical considerations:

- WEC retained Dan Brown Associates to assist with design on the project.
- Repair consisted of
  - 10-inch micropiles socketed into rock on 5’ centers
  - Alternating batter on the micropiles.
  - Micropile casing joints reinforced with outer sleeves for additional moment resistance/section modulus.
  - 80-foot, 160 kip tiebacks on 10’ centers.
  - Piles and tiebacks connected by a reinforced concrete grade beam.
  - An option to install a second row of anchors if movement is not arrested
Typical Section
Scale 1" = 3'

1. General
2. Anchor Details
3. sofa beam
4. Construction Excavation (Baffle)
5. Anchor Girders
6. Meridians Spaced at 10 ft Alternating Batter
7. Original Ground Surface

Note: All excavations shall be in accordance with final overburden.
PHASE II

• The site initially stabilized following the installation of the micropiles and tiebacks for a period of 6 months.
• Gradual movement commenced again in early 2013, coinciding with a period of record rainfall.
• WEC installed the remaining tiebacks and added horizontal drains, as the interim inclinometer data indicated that precipitation was the driving factor in re-starting the downslope movement.
Repaired Site-Introduction of Reinforcement

Past 3 Months Average Historical

Historical Poly.

Poly. (Rainfall, past 3 month avg)

Rainfall, past 3 month avg

Resisting Force, Millions #'s

Repaired Site Slope Movement, 1/10th inches

Past 3 Months Average Historical Poly. (Past 3 Months Average Historical)
Analytical considerations-DESIGN MODIFICATIONS:

- WEC made relatively low-cost modifications to the design of the additional anchors
  - Enlarged anchor pads to 7’ by 7’, adding 36% more bearing area
  - Added 2 additional strands to each anchor, allowing for 40% more tensile force to be applied.
  - Added horizontal drains to reduce pore pressures indicated to be driving slope movement.
  - Shotcreted anchor pads in place to reduce potential for disturbance.
  - Grouted existing tension cracks to reduce water infiltration.
TYPICAL SECTION

SCALE 1"=3'

NOTE: ALL EXCAVATIONS SHALL BE IN ACCORDANCE WITH OSHA REGULATIONS

CONSTRUCTION EXCAVATION (BACKFILL)

ANCHOR BLOCKS
EXACT LOCATION MAY VARY

REACTION BLOCK HEIGHT
 CHANGED TO 7'FT

GRADE BEAM

MICROPILES SPACED AT 10'FT ALTERNATING BATTER

TIEBACKS

ORIGINAL GROUND SURFACE

(APROX) 3

1
The results

• Subsequent inclinometer readings indicated measurable upslope movement, indicating the repair had overcome the driving force of the moving mass.
UPSLOPE INCLINOMETER MOVEMENT

Deflection (in)

LEGEND
- Initial: 3 Mar 2011
- 6 May 2011
- 29 Jul 2011*
- 26 Aug 2011
- 30 Sep 2011
- 11 Nov 2011
- 9 Dec 2011
- 16 Jan 2012
- 23 Jun 2012
- 10 Aug 2012
- 19 Sep 2012
- 18 Oct 2012
- 6 Dec 2012
- 6 Mar 2013
- 19 Jun 2013
- 2 Jul 2013
- 14 Aug 2013
- 15 Nov 2013
- 19 Dec 2013
- 20 May 2014
- 25 Jul 2014
UN-REPAIRED SITE-SIMILARITIES

• The second site is also located on the lakeshore, approximately 1 mile from the repaired site.
• Weather patterns are similar at both sites
• Both sites are relatively gently sloping
• Inclinometer data suggests that both sites are highly sensitive to precipitation/pore water pressure
• Both sites exhibit silty sands with unusually low fines contents at depth (10% passing)
• Both sites exhibited similar rates of movement pre-repair
UN-REPAIRED SITE-OBSERVATIONS

• Significant data gaps exist in the unrepaired site inclinometer readings
• Anecdotal information indicates movement slowed to a near standstill during 2013
• Site observations indicate movement resumed in 2013 (Record rainfall), and total movements during the year may have been on the order of 6 inches or more
• Weekly readings during December 2013 indicate as much as 0.5” of movement over a 1-month period.
• Readings during the same month at the repaired site indicated movements on the order of 0.1” during the same timeframe.
• Partial repairs obviously had a significant arresting downslope movement even during periods of slope saturation.
3 Month Rainfall vs Average

Rainfall, past 3 month avg
Past 3 Months Average Historical
Poly. (Rainfall, past 3 month avg)
Poly. (Past 3 Months Average Historical)
Repaired Site-Movement VS Time

- **Repaired Site Slope Movement, 1/10th inches**
- **Rainfall, past 3 month avg**
- **Past 3 Months Average Historical**
- **Poly. (Rainfall, past 3 month avg)**
- **Poly. (Past 3 Months Average Historical)**
Repaired Site—Introduction of Reinforcement

- Repaired Site Slope Movement, 1/10th inches
- Resisting Force, Millions #’s
- Rainfall, past 3 month avg
- Past 3 Months Average Historical
- Poly. (Rainfall, past 3 month avg)
- Poly. (Past 3 Months Average Historical)
Repaired Site – Instrumented Micropile

- Repaired Site Slope Movement, 1/10th inches
- Resisting Force, Millions #’s
- Rainfall, past 3 month avg
- Past 3 Months Average Historical
- Poly. (Rainfall, past 3 month avg)
- Poly. (Past 3 Months Average Historical)
Unrepaired Site-Rainfall VS Movement

- **Rainfall, past 3 month avg**
- **Unrepaired Site Slope Movement, 1/10th inches**
- **Past 3 Months Average Historical**
- **Poly. (Rainfall, past 3 month avg)**
- **Poly. (Unrepaired Site Slope Movement, 1/10th inches)**
- **2 per. Mov. Avg. (Unrepaired Site Slope Movement, 1/10th inches)**
- **Poly. (Past 3 Months Average Historical)**
Repaired Trend VS Unrepaired Trend

Repaired Site Slope Movement, 1/10th inches
Unrepaired Site Slope Movement, 1/10th inches
Resisting Force, Millions #'s
Poly. (Repaired Site Slope Movement, 1/10th inches)
2 per. Mov. Avg. (Unrepaired Site Slope Movement, 1/10th inches)