Questions for ITRS

- What standards are currently used for high lines?
- Do you have any photos from your high line operations?
- Have you seen any high line failures?
- Have you heard about any high line failures?
- Can you describe any training that you or your team has received for high lines?
- How do you anchor your high lines?
- What ropes do you use for high lines?
- What loads do you allow on high lines (i.e., one rescuer + patient + litter)?
- What is the longest highline you have used in practice?
- What is the longest highline you have used during a real mission?
- How many missions/rescues has your team used a high line or a guide line?
- Do you use load cells as part of your highline training or on missions?

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Failing is not generally an option

- Track line failure South America

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Definitions

- Track Line, Guide Line, High Line, Slack Line, Sky lines, etc...
- ...for purposes of rescue and climbing application, we are talking about two loaded anchor points joined by a rope to move a load across a chasm or over an obstacle.

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Project Goals

- Determine a method for predicting through calculation the rope tensions on a track line.
- Determine if the method works (build it, measure the loads throughout the system, update the model).
- Use the resulting mathematical model to consider a wide range of combinations of loads and geometries.
- Determine if the current rules of thumb as published and taught in the rescue/highline guidelines are conservative
- Determine conditions (loads + geometries) that are unsafe

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Examples of Track Line Use

Lechugilla

Saxon, Suisse, 1926

Steve Sonntag

200m guiding line
On Rescue, Sandias, NM

Pre-tension Rules of Thumb (2:1)

• Pre-tension the system with two people (~100 lbs)
• Empirical method that works for 1 kN load with 11 mm rope.
• May not work for sloping system
• May not work for stiff rope

Post-tension Rules of Thumb
Factor Rule (12:1 and 18:1)

• Assume a 10:1 static safety factor
• Pull tension into the system after the load is at the center of the span
• Limit the tension in system by limiting the number of people that can haul on the system:
  - 12 people (~600 lbs) for an 11 mm rope
  - 18 people for 12.5 mm rope
  - Or a MA to create the same as above (i.e.: 4 people on 3:1 = 12)
• This method works, but has limits:
  - The load must be in the center of the span...how do you know?
  - The track line is assumed horizontal
  - The sag is not known until the system is tested and fully tensioned
  - The center of the span may not be known on a sloping line

Confusion Exists


• “Based on empirical testing, the average person exerts about 100 lbs of force when pulling with a glove hand and moderate effort.”
• “For 11 mm (7/16”) rope in order to maintain about a 5:1 system safety factor, it is recommended to limit the load to 1200 lbs of force, or 12 people. For 12.5 mm (1/2”) rope the factor is 18 people or 1800 lbs.”

This is in conflict with On Rope and Rigging for Rescue:
• “The Kootenay High Line System (KHS) is intended to be operated with a Static System Safety Factor of 10:1 or greater on the track rope.”
• There also is confusion about when the “12 people” haul load is applied – it must be applied when the load is at the center of the span...ask Vince.
Rules of Thumb: 10% Rule

- For every 200 lbs with 100 feet of span, there should be a sag of 10%
  - The rope sag is the visible sag in the main line before the load is applied

\[
\text{Initial Sag} = \frac{\text{Load (lbs)}}{200 (lbs)} \times \frac{\text{span}}{100'} \times 0.1
\]

This method may be very conservative
For long spans the sag may be hard to estimate due to catenary effect
When load is applied, more sag will occur

Methods

Process of building a computer model, and the interplay between experiment, simulation, and theory.

Diablo Canyon Highline Research Center

Engineering Statics

Tension is a Function of Sag

- Predicting sag is important for two reasons:
  - Too little sag results in too much tension
  - Too much sag causes the load to contact the ground

Load as a function of angle

<table>
<thead>
<tr>
<th>Angle (degrees)</th>
<th>Load (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
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<tr>
<td>170</td>
<td>145</td>
</tr>
<tr>
<td>180</td>
<td>145</td>
</tr>
</tbody>
</table>

T=0.71X
T=1.0X
T=1.66X
T=0.54X
Simple math: may be wrong

Load will be maximum at center of span
Sag is not known until load is at center span
Rope length is the "stretched" rope length, not the distance between spans

Catenary

- A catenary is the curve that an idealized hanging chain or cable assumes under its own weight when supported only at its ends
- For short systems the catenary effect may not be important
- For long systems, curvature of the rope and the rope weight may be important
- Using a catenary allows us to compute the unloaded sag in the rope due to self weight

Catenaries

- At any point along a catenary the slope defines the ratio of the tension acting in the x and y direction

Catenaries

- Given rope weight and point loads, the path \( y(x) \) can be computed if the initial slope is known
- Iterate the initial slope for a given rope length such that the final point \( y \) is at the correct height of anchor 2
- The length of rope will be a function of the tension in the rope.

Rope Stretch

Assume a second order rope fit based on Attaway and Weber, ITRS 2002

\[
F = \frac{k_a}{L} \delta + \frac{k_b}{L} \delta^2
\]

Solve using quadratic
Rope Stretch and Rope Path
Length Must be Equal

\[ L_{\text{stretched}} = \sum \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} = L_{\text{actual}} = L + \frac{d_k}{2k_b} \]

We compute rope length based on the stretch from given tension
And we compute the rope length based on a catenary path for a given tension
For one tension, the rope length for both the catenary path and the stretched rope will be the same – this will be the tension of the system.
Once the tension is known, the sag can be computed.

Examples
- Span width = 84 m
- Span angle = 11 degrees
- Load = 1 MB = 95 kN
- Rope 11 mm PMI EZ (nylon)
- Pre-tension 2:1 with one hauler = 45 kN

Prediction: preload of 0.45 kN

Rope deflects 2.5 m from the straight line path
Rope initial length = 83.9 m, stretch length = 85.79 m

Prediction: Deflection under 0.95 kN load

Rope deflects ~8 m from the straight line path
Rope initial length = 83.9 m, stretch length = 87.6 m

Prediction: Rope load as a function of span location

The anchor loads (track line + haul line) are shown in the plot.
The haul line represents the force need to keep the load from sliding to the center of the sag.
The tension in the system will be the minimum of the anchor loads.

Examples
- Span width = 84 m
- Span angle = 11 degrees
- Load = 1 MB = 95 kN
- Rope 11 mm PMI EZ (nylon)
- Pre-tension 2:1 with one hauler = 45 kN
Examples

- Span width = 84 m
- Span angle = 11 degrees
- Load = 1 MB = .95 kN
- Rope 11 mm PMI EZ (nylon)
- Pre-tension 2:1 with one hauler = .45 kN

Examples

- Span width = 84 m
- Span angle = 11 degrees
- Load = 1 MB = .95 kN
- Rope 11 mm PMI EZ (nylon)
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- Pre-tension 2:1 with one hauler = .45 kN

Measure vs. Predicted

- Loads were measured using a load cell on the track line at one anchor.
- Agreement was within 5% at center of span.
- Error was larger near the start and end of the span (10%).
- Likely source of the error was stiffness of the tag line not included in calculations.

Excellent agreement between predicted and measured deflections.
What is safe?

- Risk = probability * consequence * ignorance
- Standard accepted practice is to use a 10:1 static safety factor for system design
- Some team will work with a lower safety factor if the situation demands accepting more risk
- A large SSF must account for dynamic loads, variations in rope strength/stiffness, unexpected loads (wind), and other unknowns

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**Prusiks Are Unpredictable**

- “A single haul prusik acts as a clutch and alerts the haul team to over tensioning when a slip occurs.”
- “Tandem Prusik Clutch at 10-14 KN; Single Prusik Clutch at 9-13 KN”
- “short Prusik failed at 28.41 kN”

**Prusiks – the weak link?**

- The track line is only as strong as its weakest link; “prusiks would appear to be our main weak link in rescue systems” (Willard, 1987).
- Prusik meta-analysis showing 1 in 5 fail, n=187 (Stiller, 2000).
- Prusiks as part of the high line tie-off may limit the system strength.
- Assuming that prusiks will slip and act as a clutch under high loads has not been supported through testing.
Too much slip?

"The tandem prusiks grip the rope without compromising its strength and if the system is overloaded, the prusiks will slip before the rope breaks adding more rope to the tensioned line, thus reducing the angle of the track line and the amount of force on each anchor."

Approximately 3.0 meters of slip is required to change the tension from 1250 lbs to 800 lbs.

Possible Prusik Alternatives

Five “feet of Rope” effect

Double Track Line using Pinned Knot Passing Pulley

Quiz: What rules to follow ?

What is the inefficiency ?  What's the system ?  How heavy is the load ?

What are the conditions ?  How much equipment do you have ?

How many people on the haul ?

Summary

- The static safety factor will not be meet for any system where prusiks are used.
- 2:1 Rules of thumb appears OK for a load of 1 kN with 11 mm nylon rope
- 2:1 Rule does not work for 2 kN load
- One meter of slack is needed for a 2 kN load
- 2:1 Rule of thumb appears OK for a 2 kN load with a 12.5 mm nylon rope.
Warnings

• “Based on empirical testing, the average person exerts about 100 lbs of force when pulling with a glove hand and moderate effort.”
• “For 11mm (7/16”) rope in order to maintain about a 5:1 system safety factor, it is recommended to limit the load to 1200 lbs of force, or 12 people. For 12.5 mm (1/2”) rope the factor is 18 people or 1800 lbs.”

If prusiks are used as part of the above system, then a PSSF of less than 2.0 will exist. Since dynamic loads of 1.6X to 2X are typical, we would expect prusik slippage on systems rigged using the above guidelines.

Warnings: The 2:1 Rule of thumb appears to place high forces on the anchors when using a polyester/blend rope.

Polyester is … stiff, like chain

Typical 2.0 kN rescue load

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<tr>
<th></th>
<th>Polyester</th>
<th>Nylon</th>
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<tbody>
<tr>
<td>11</td>
<td>2.0 kN</td>
<td>0.45 kN</td>
</tr>
<tr>
<td>10</td>
<td>2.0 kN</td>
<td>0.45 kN</td>
</tr>
<tr>
<td>Tallon</td>
<td>2.0 kN</td>
<td>0.45 kN</td>
</tr>
<tr>
<td></td>
<td>6.60</td>
<td>2.29</td>
</tr>
<tr>
<td></td>
<td>6.20</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>9.00</td>
<td>2.87</td>
</tr>
</tbody>
</table>

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