# Engineering Geology of a Basalt Landslide Complex, Black Mountain, Mojave Desert, California

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A previously unmapped landslide complex of Pliocene-age basalt debris exists on Black Mountain in the eastern Mojave Desert, 11 kilometers (7 miles) north of Barstow, California. The landslide complex is a combination of a translational slide and a wedge failure controlled by three joint sets and parallel flow planes. To determine structural controls, the method of slope failure, and the stability of nearby slopes, I mapped, constructed cross sections, and calculated slope stability using a simplified Swedish Slice method. Failure occurred along out-of-slope dipping flow planes, which have a greater apparent dip in the slide area than adjacent slopes. The increased apparent dip is due to a change in slope aspect. Based on my calculations, the adjacent slopes unaffected by landsliding remain highly unstable.

## Introduction

Pliocene-aged basalt flows on the southwest side of Black Mountain, located in the Mojave Desert north of Barstow California, have failed in a complex landslide. The multiple slides are adjacent to and on top of each other in a relatively small area Figure 1. This slide complex appears to be unique in the area, as no other basalt landslides have been mapped on Black Mountain or any nearby mountains.[1] This landslide complex appears to have not been previously mapped despite its obvious geomorphic features and expression on aerial photographs and topographic maps.

The isolated, unique nature, and lack of previous documentation highlights the need to understand the mechanics and possible triggers for this slide complex. Basalt flows cover large areas in the Mojave Desert[1] and understanding what forces caused this particular basalt slope to fail is important for safety of future homes, as development expands in the region. The geology and mechanics of this slide may indicate if the slide was triggered by wetter climatic conditions or earthquake shaking.

This study presents: (1) a geologic map of the slide complex, (2) geologic cross sections and structure stereonet diagrams of bedding planes and joints surrounding the slide complex, and (3) slope stability calculations for the slope failure.

## Background

The term ''landslide'' refers to mass movement that occurs along a distinct zone of weakness that that separates the slide material from underlying material.[2,3] The two main types of landslides are rotational and translational.[3]

Landslides occur when the gravitational or driving forces of material exceeds the shear strength or resisting forces.[2] Gravity is the main driving force, and the resisting force is generated by cohesion of the material and friction along the slip surface. Landslides typically occur when the resisting force is reduced. The main triggers of landslides are as follows: an increase of hydrostatic pressure, removal of toe material (resisting buttress), reduction in normal stress by earthquake shaking, and reduction in material shear strength by weathering.[3] A tuff layer, for instance, can weather to clay, which has a very low angle of internal friction, and can cause a slope to become highly unstable. When the resisting force divided by the driving force is less than one, landsliding will occur.

### *Geologic Setting*

The Mojave Desert is located in Southern California, south of the Great Basin Desert and north of the Sonoran Desert. The Mojave consists of more than 66,000 $km^2$ (25,000 $mi^2$) of primarily basins and ranges, and is the smallest of the four North American deserts. Average annual rainfall at Barstow is 111 millimeters per year (4.40 inches) as a result of rain shadowing from the Central and Eastern Transverse Ranges.

During the Pleistocene, the Mojave Desert was wetter and colder.[4] This region received greater amounts of rainfall and large lakes and rivers developed. In the Holocene, the climate became warmer and dryer, as it is today.

Volcanism in the Mojave Desert began in the mid-Jurassic, with the youngest eruption only 8,000 years before present. The basalt of Black Mountain was originally estimated to be Pleistocene in age.[1] More recent studies date, the upper flows of the Black Mountain basalt field, to the northeast of Harper Valley from 3.56 ± 0.08 to 3.74 ± 0.05 Ma (whole rock $^{40}Ar/^{39}Ar$).[5] The basalt is surrounded by Quaternary alluvium and is partially buried by wind blown sand. The landslide area lies just above the inferred elevation of Pleistocene Harper Lake, whose playa is to the southwest.[1]

The western edge of the Mojave is bound by the San Andreas Fault to the southwest and the Garlock Fault to the northwest. The western half of the Mojave is in the Eastern California Shear Zone (ECSZ), which accounts for 9-23% of the total Pacific North American plate motion.[5] Northwest trending, right lateral strike slips faults dominate the ECSZ. Active tectonics of the ECSZ created the basins and ranges in the Mojave beginning ~ 18.5 Ma and continues today.[1] Black Mountain is cut by at least one northwest trending, right-lateral strike-slip fault.[1]

| | Flow Planes. | NW Trending Joints. | NE Trending Joints. | NS Trending Joints. |
|---|---|---|---|---|
| Average Strike. | N 56 W | N 32 W | N 57 E | N 2 S |
| Average Dip. | 20 S | 59 S | 61 N | 77 E |

Tablre 1 Average Strike and Dip in Landslide Area

## Methods

A geologic and structure map of the landslide complex and surrounding region Figure 1 was constructed using stereographic aerial photographs and the 1:24,000 scale Water Valley topographic quadrangle. Joint and flow plane attitudes were measured using with a Brunton compass and locations were plotted using a Global Positioning System (G.P.S.) receiver. These data were compiled on four lower projection stereonet diagrams Figure 2. Two cross-sections were constructed; one through the slide area Figure 3, and the other through an adjacent, intact slope Figure 4.

Slope stability was calculated using a simplified Swedish Slice method under saturated and dry conditions for both the failed slope Figure 3 and the intact slope Figure 4. The calculations are done in English units because the topography is in feet. Inputs for the stability calculation are provided Figure 5-6. The unsaturated weight of the basalt is 26.5 $kN/m^3$ (169.4 $lbs/ft^3$) and the saturated weight is 27.6 $kN/m^3$ (175.6 $lbs/ft^3$), with an estimated porosity of 10 %. A cohesion value of 4.7 kPa (100 $lbs/ft^2$) was used in the stability calculations and the factor of safety was driven to 1 (the failure limit) by adjusting the angle of internal friction. The relatively low cohesive strength is inferred because of the pervasive joint and flow banding planes in the basalt.

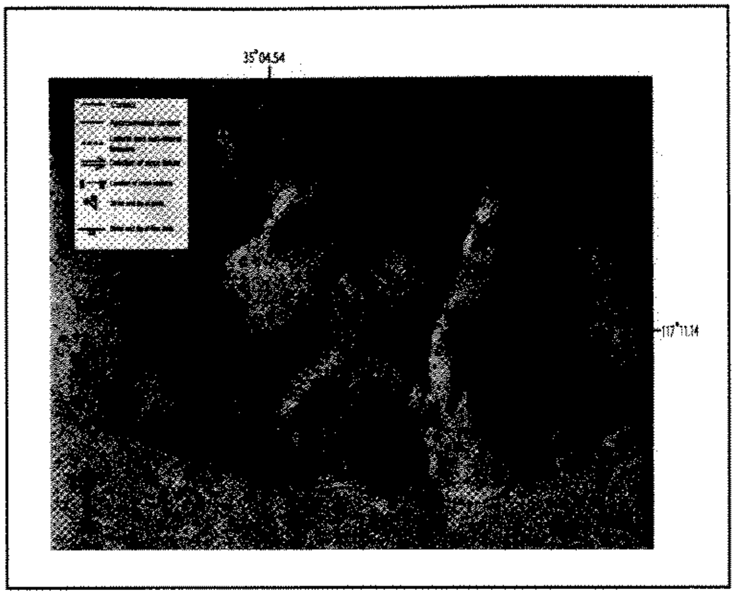


Figure 1 Geologic map of the landslide complex, northeast Harper Valley, California. Base is U.S. Geological Survey aerial photograph NAPP, 6855-64, 05-29-94.

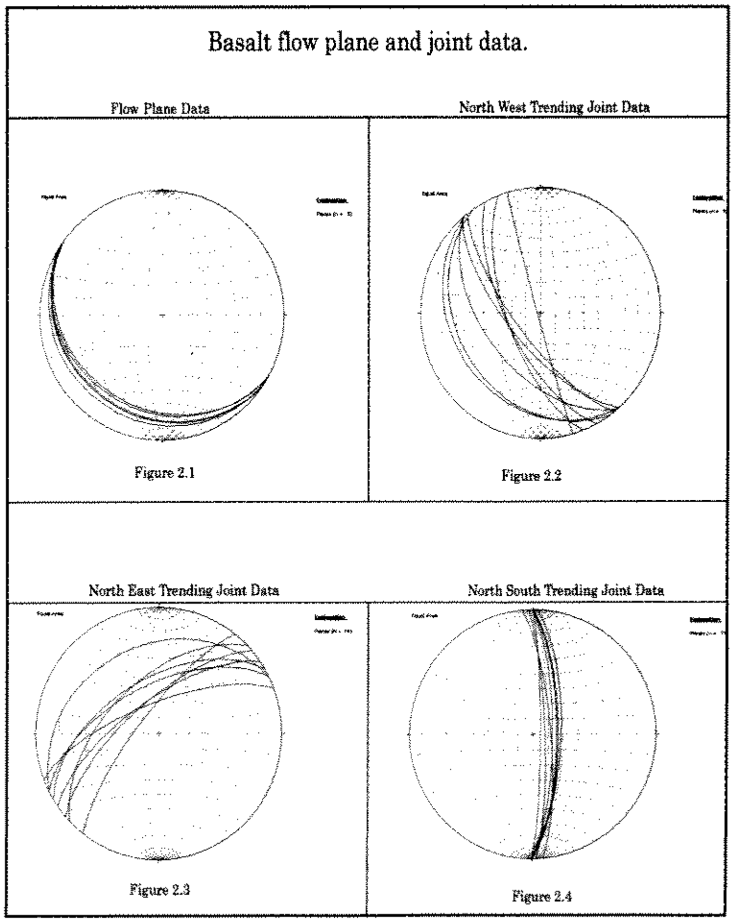


Figure 2 Lower projection stereonet data from the landslide area. Each diagram illustrates the distribution of a different data set from flow plane (2.1) to joints (2.2-2.4).

The type of slide and the possible mechanism of failure were interpreted from cross sections, aerial photographs, and topography. Site reconnaissance also played a large part in determining the type of slide and how well the slide was structurally controlled.

## Results

The Black Mountain basalt is dark black, intermittently vesicular, and very fine-grained. The major minerals are plagioclase (labradorite), pyroxene, and small amounts of olivine and iron oxides.[1] Vesicles range in size from a few millimeters to 9 cm long and compose 5-25 % of total rock volume. Vesicles are elongate and the basalt has ropy pahoehoe features. Within the study area, basalt flow planes and joints are visible in the outcrops surrounding the landslide. The Black Mountain basalt is a thin sheet less than 30.5 m (100 ft). thick, and conformably overlays the Pliocene aged Ricardo Formation.[1]

The basalt has three prominent joint planes and multiple parallel flow planes. As suggested by the stereonet plots Figure 2, the joint and flow plane data are strongly consistent. The average strike and dip measurements of the three joint and flow planes are presented in Table 1. These average measurements were used in calculating apparent dips for the cross sections. The apparent dip of the joints and flow planes are critical in understanding why this landslide occurred.

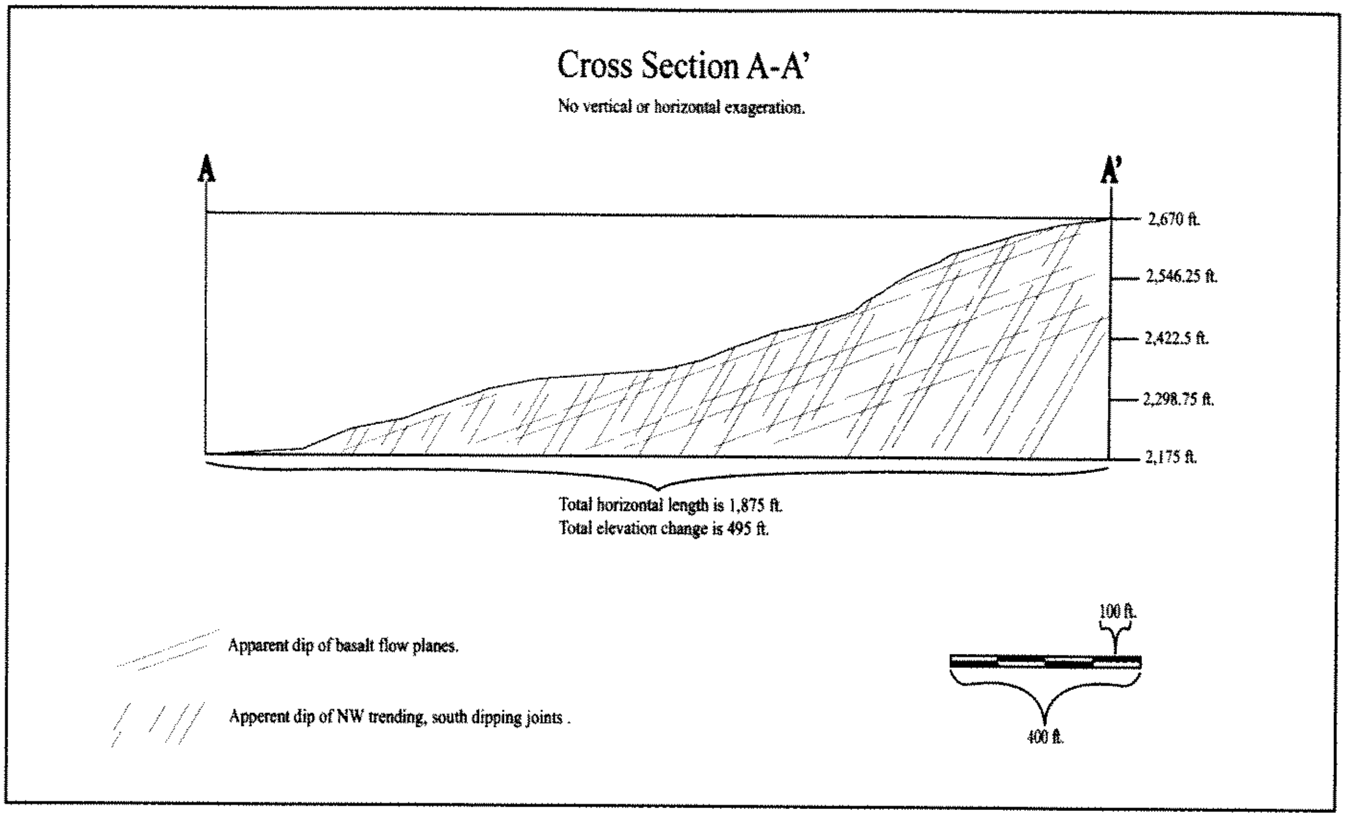


Figure 3 Geologic cross section A-A' through Qls 1 (see Figure 1 for location).

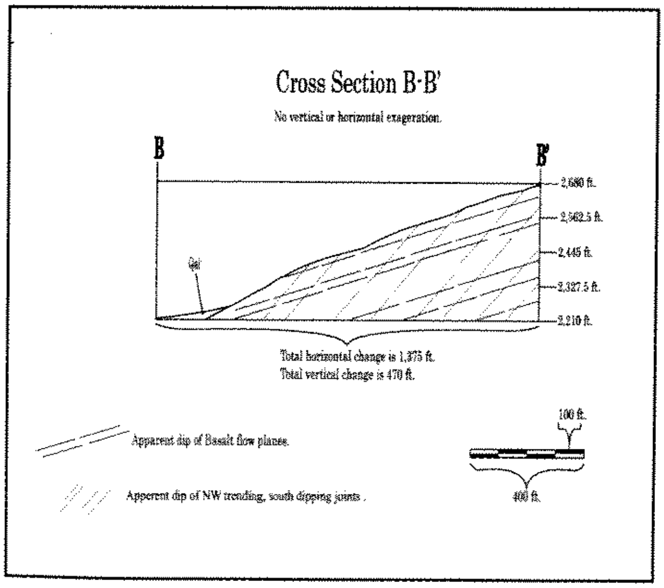


Figure 4 Geologic cross section B-B' through intact slope located southeast of Qls 1 (see Figure 1 for location).

The apparent dip of the flow planes through cross section A-A' Figure 3 is 18.8 degrees and the apparent dip through the intact slope, cross section B-B', Figure 4 is 16.8 degrees. The equation for determining apparent dip is: *Tan (apparent dip) = Tan (true dip) * Sin (angle between strike and cross section)*

The basalt landslide complex is partially covered by wind blown sand from the nearby playa. The landslide complex has a steep toe (~30 degrees) and a relatively flat main body. Transverse cracks partially filled with wind blown sand are visible in the aerial photographs. The head scarp and lateral margins are nearly vertical, with the

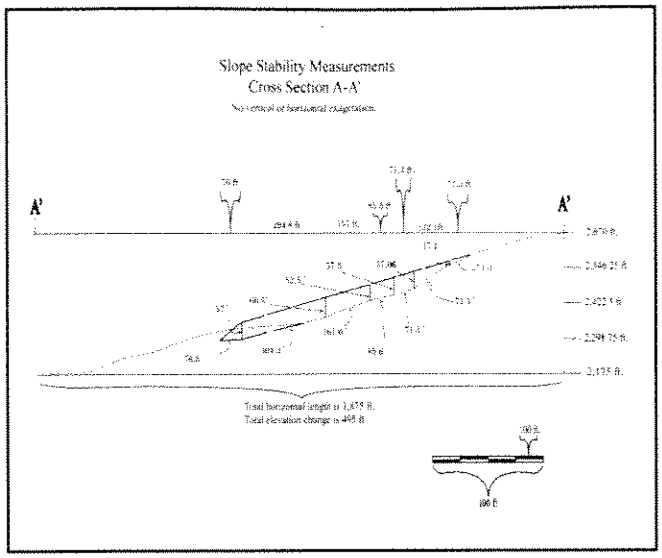


Figure 5 Swedish Slice Method analysis of reconstructed landslide.

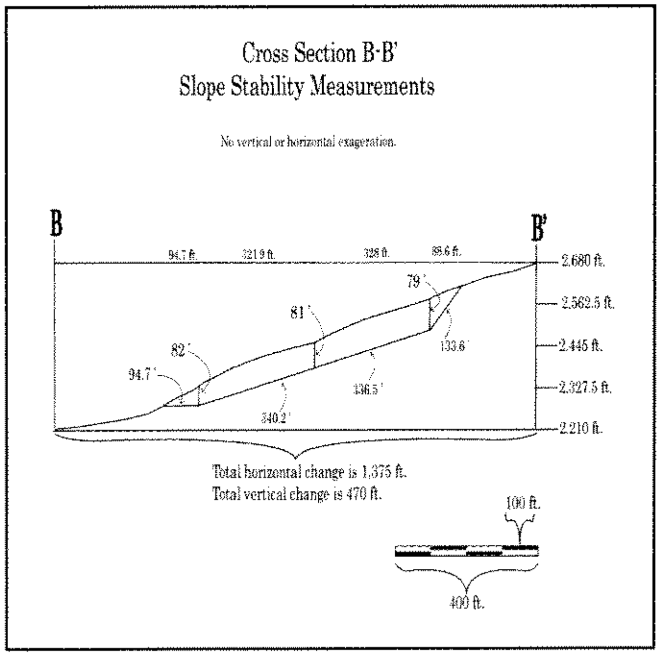
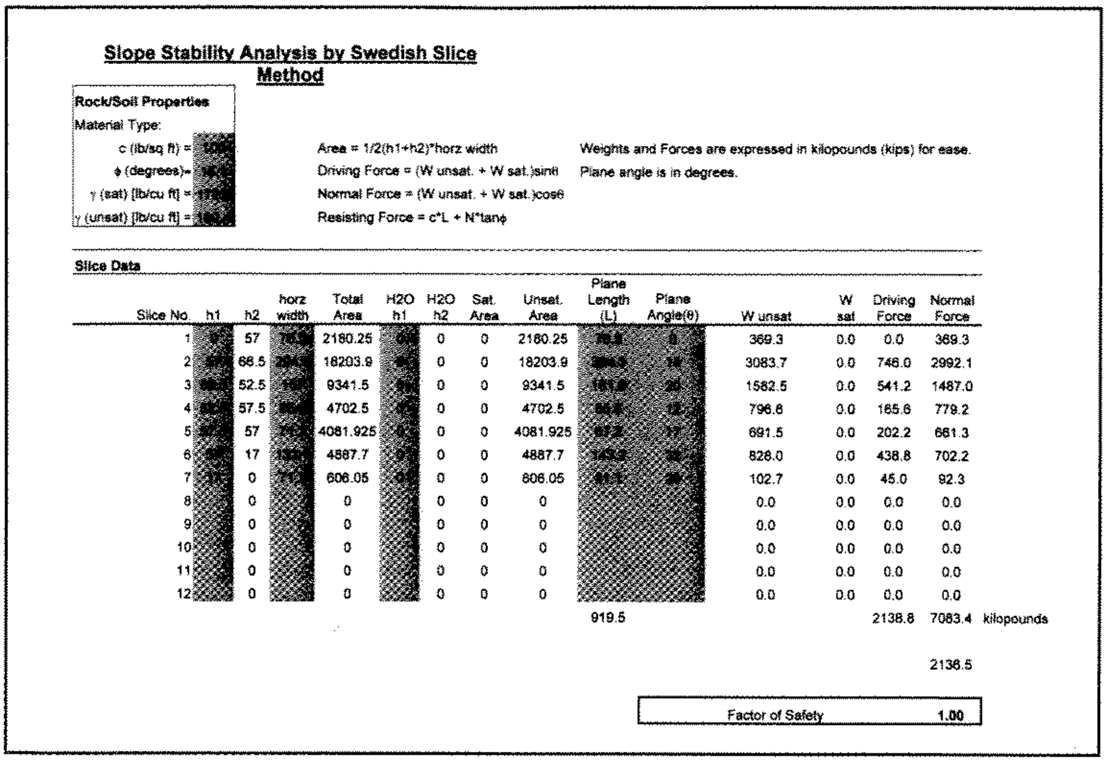


Figure 6 Swedish Slice Method analysis for intact slope.

head scarp also exhibiting an arcuate shape. Any slide plane exposed at the surface has been covered in wind blown sand.

When reconstructing the landslide area I find that the slope, during dry conditions (no groundwater), would have been stable with angles of internal friction above 16.1 degrees. When the reconstructed slope is saturated, the landslide area would have been stable only if the angles of internal friction were greater than 24.3 degrees Figure 7-8.

Calculations for the adjacent intact slope Figure 6 indicate the angles of internal friction must be greater than 17.4 degrees, assuming dry conditions. If the slope is stable during saturated conditions, the angles of internal friction must be greater than 25.8 degrees Figure 9-10.



**Slope Stability Analysis by Swedish Slice Method**

**Rock/Soil Properties**
Material Type:
c (lb/sq ft) = [illegible]
ϕ (degrees)= [illegible]
γ (sat) [lb/cu ft] = [illegible]
γ (unsat) [lb/cu ft] = [illegible]

Area = 1/2(h1+h2)*horz width
Driving Force = (W unsat. + W sat.)sinθ
Normal Force = (W unsat. + W sat.)cosθ
Resisting Force = c*L + N*tanϕ

Weights and Forces are expressed in kilopounds (kips) for ease.
Plane angle is in degrees.

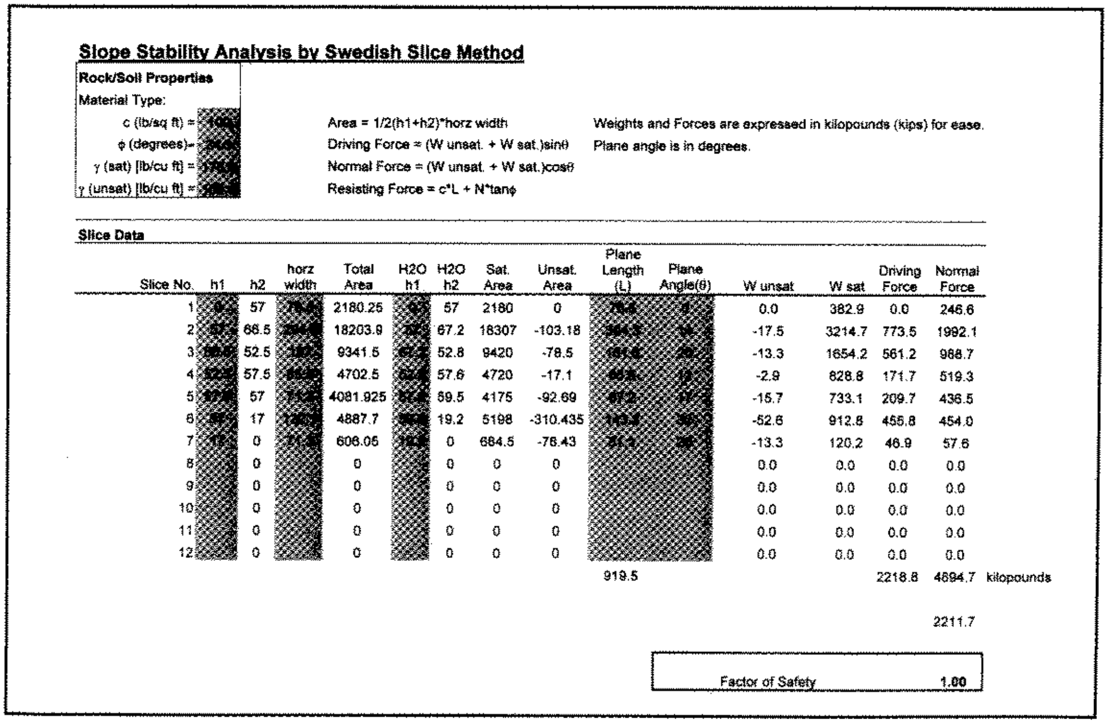
**Slice Data**

| Slice No. | h1 | h2 | horz width | Total Area | H2O h1 | H2O h2 | Sat. Area | Unsat. Area | Plane Length (L) | Plane Angle(θ) | W unsat | W sat | Driving Force | Normal Force |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | [illegible] | 57 | [illegible] | 2180.25 | [illegible] | 0 | 0 | 2180.25 | [illegible] | [illegible] | 369.3 | 0.0 | 0.0 | 369.3 |
| 2 | [illegible] | 66.5 | [illegible] | 18203.9 | [illegible] | 0 | 0 | 18203.9 | [illegible] | [illegible] | 3083.7 | 0.0 | 746.0 | 2992.1 |
| 3 | [illegible] | 52.5 | [illegible] | 9341.5 | [illegible] | 0 | 0 | 9341.5 | [illegible] | [illegible] | 1582.5 | 0.0 | 541.2 | 1487.0 |
| 4 | [illegible] | 57.5 | [illegible] | 4702.5 | [illegible] | 0 | 0 | 4702.5 | [illegible] | [illegible] | 796.8 | 0.0 | 165.6 | 779.2 |
| 5 | [illegible] | 57 | [illegible] | 4081.925 | [illegible] | 0 | 0 | 4081.925 | [illegible] | [illegible] | 691.5 | 0.0 | 202.2 | 661.3 |
| 6 | [illegible] | 17 | [illegible] | 4887.7 | [illegible] | 0 | 0 | 4887.7 | [illegible] | [illegible] | 828.0 | 0.0 | 438.8 | 702.2 |
| 7 | [illegible] | 0 | [illegible] | 606.05 | [illegible] | 0 | 0 | 606.05 | [illegible] | [illegible] | 102.7 | 0.0 | 45.0 | 92.3 |
| 8 |  | 0 |  | 0 |  | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |
| 9 |  | 0 |  | 0 |  | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |
| 10 |  | 0 |  | 0 |  | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |
| 11 |  | 0 |  | 0 |  | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |
| 12 |  | 0 |  | 0 |  | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |
|  |  |  |  |  |  |  |  |  | 919.5 |  |  |  | 2138.8 | 7083.4 kilopounds |

2136.5

Factor of Safety 1.00

Figure 7 Slope stability calculation for slope B-B' completely dry, driven to failure



**Slope Stability Analysis by Swedish Slice Method**

**Rock/Soil Properties**
Material Type:
c (lb/sq ft) = [illegible]
ϕ (degrees)= [illegible]
γ (sat) [lb/cu ft] = [illegible]
γ (unsat) [lb/cu ft] = [illegible]

Area = 1/2(h1+h2)*horz width
Driving Force = (W unsat. + W sat.)sinθ
Normal Force = (W unsat. + W sat.)cosθ
Resisting Force = c*L + N*tanϕ

Weights and Forces are expressed in kilopounds (kips) for ease.
Plane angle is in degrees.

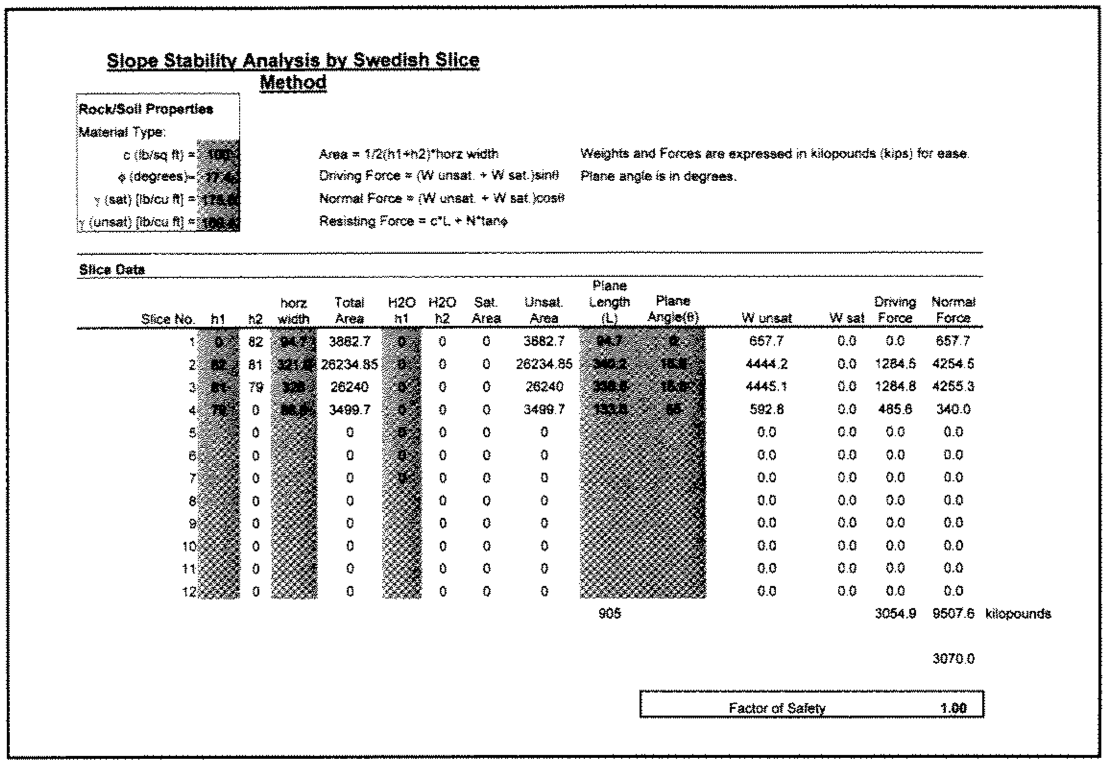
**Slice Data**

| Slice No. | h1 | h2 | horz width | Total Area | H2O h1 | H2O h2 | Sat. Area | Unsat. Area | Plane Length (L) | Plane Angle(θ) | W unsat | W sat | Driving Force | Normal Force |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | [illegible] | 57 | [illegible] | 2180.25 | [illegible] | 57 | 2180 | 0 | [illegible] | [illegible] | 0.0 | 382.9 | 0.0 | 246.6 |
| 2 | [illegible] | 66.5 | [illegible] | 18203.9 | [illegible] | 67.2 | 18307 | -103.18 | [illegible] | [illegible] | -17.5 | 3214.7 | 773.5 | 1992.1 |
| 3 | [illegible] | 52.5 | [illegible] | 9341.5 | [illegible] | 52.8 | 9420 | -78.5 | [illegible] | [illegible] | -13.3 | 1654.2 | 561.2 | 988.7 |
| 4 | [illegible] | 57.5 | [illegible] | 4702.5 | [illegible] | 57.6 | 4720 | -17.1 | [illegible] | [illegible] | -2.9 | 828.8 | 171.7 | 519.3 |
| 5 | [illegible] | 57 | [illegible] | 4081.925 | [illegible] | 59.5 | 4175 | -92.69 | [illegible] | [illegible] | -15.7 | 733.1 | 209.7 | 436.5 |
| 6 | [illegible] | 17 | [illegible] | 4887.7 | [illegible] | 19.2 | 5198 | -310.435 | [illegible] | [illegible] | -52.6 | 912.8 | 455.8 | 454.0 |
| 7 | [illegible] | 0 | [illegible] | 606.05 | [illegible] | 0 | 684.5 | -78.43 | [illegible] | [illegible] | -13.3 | 120.2 | 46.9 | 57.6 |
| 8 |  | 0 |  | 0 |  | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |
| 9 |  | 0 |  | 0 |  | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |
| 10 |  | 0 |  | 0 |  | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |
| 11 |  | 0 |  | 0 |  | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |
| 12 |  | 0 |  | 0 |  | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |
|  |  |  |  |  |  |  |  |  | 919.5 |  |  |  | 2218.8 | 4894.7 kilopounds |

2211.7

Factor of Safety 1.00

Figure 8 Slope stability calculations for landslide A-A' fully saturated, driven to failure.



**Slope Stability Analysis by Swedish Slice Method**

**Rock/Soil Properties**
Material Type:
c (lb/sq ft) = 100
ϕ (degrees)= 17.4
γ (sat) [lb/cu ft] = 175.6
γ (unsat) [lb/cu ft] = 169.4

Area = 1/2(h1+h2)*horz width
Driving Force = (W unsat. + W sat.)sinθ
Normal Force = (W unsat. + W sat.)cosθ
Resisting Force = c*L + N*tanϕ

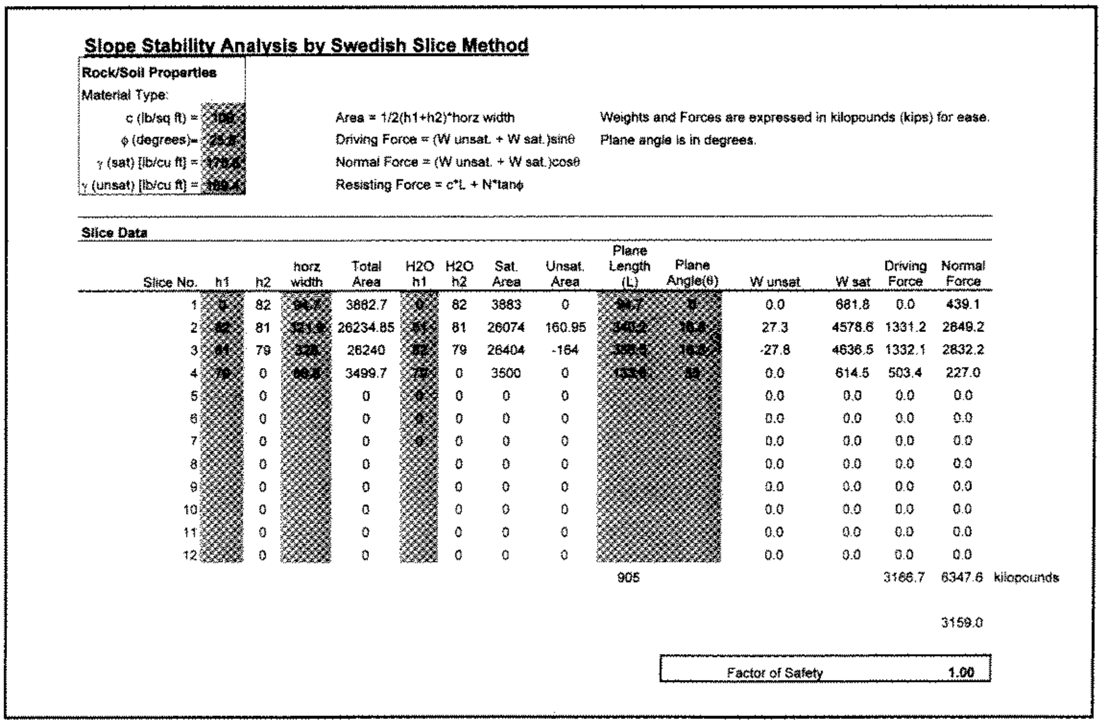
Weights and Forces are expressed in kilopounds (kips) for ease.
Plane angle is in degrees.

**Slice Data**

| Slice No. | h1 | h2 | horz width | Total Area | H2O h1 | H2O h2 | Sat. Area | Unsat. Area | Plane Length (L) | Plane Angle(θ) | W unsat | W sat | Driving Force | Normal Force |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 82 | 94.7 | 3882.7 | 0 | 0 | 0 | 3882.7 | 94.7 | 0 | 657.7 | 0.0 | 0.0 | 657.7 |  |
| 2 | 82 | 81 | 321.9 | 26234.85 | 0 | 0 | 0 | 26234.85 | 340.2 | 16.8 | 4444.2 | 0.0 | 1284.5 | 4254.5 |  |
| 3 | 81 | 79 | 328 | 26240 | 0 | 0 | 0 | 26240 | 338.6 | 16.8 | 4445.1 | 0.0 | 1284.8 | 4255.3 |  |
| 4 | 79 | 0 | 88.6 | 3499.7 | 0 | 0 | 0 | 3499.7 | 133.6 | 55 | 592.8 | 0.0 | 485.6 | 340.0 |  |
| 5 |  | 0 |  | 0 | 0 | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |  |
| 6 |  | 0 |  | 0 | 0 | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |  |
| 7 |  | 0 |  | 0 | 0 | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |  |
| 8 |  | 0 |  | 0 |  | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |  |
| 9 |  | 0 |  | 0 |  | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |  |
| 10 |  | 0 |  | 0 |  | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |  |
| 11 |  | 0 |  | 0 |  | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |  |
| 12 |  | 0 |  | 0 |  | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |  |
|  |  |  |  |  |  |  |  |  | 905 |  |  |  | 3054.9 | 9507.6 | kilopounds |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3070.0 |  |

Factor of Safety 1.00

Figure 9 Stability calculations for slope B-B' completely dry, driven to failure.



**Slope Stability Analysis by Swedish Slice Method**

**Rock/Soil Properties**
Material Type:
c (lb/sq ft) = 100
ϕ (degrees)= 25.8
γ (sat) [lb/cu ft] = 175.6
γ (unsat) [lb/cu ft] = 169.4

Area = 1/2(h1+h2)*horz width
Driving Force = (W unsat. + W sat.)sinθ
Normal Force = (W unsat. + W sat.)cosθ
Resisting Force = c*L + N*tanϕ

Weights and Forces are expressed in kilopounds (kips) for ease.
Plane angle is in degrees.

**Slice Data**

| Slice No. | h1 | h2 | horz width | Total Area | H2O h1 | H2O h2 | Sat. Area | Unsat. Area | Plane Length (L) | Plane Angle(θ) | W unsat | W sat | Driving Force | Normal Force |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 82 | 94.7 | 3882.7 | 0 | 82 | 3883 | 0 | 94.7 | 0 | 0.0 | 681.8 | 0.0 | 439.1 |  |
| 2 | 82 | 81 | 321.9 | 26234.85 | 81 | 81 | 26074 | 160.95 | 340.2 | 16.8 | 27.3 | 4578.6 | 1331.2 | 2849.2 |  |
| 3 | 81 | 79 | 328 | 26240 | 82 | 79 | 26404 | -164 | 338.6 | 16.8 | -27.8 | 4636.5 | 1332.1 | 2832.2 |  |
| 4 | 79 | 0 | 88.6 | 3499.7 | 79 | 0 | 3500 | 0 | 133.6 | 55 | 0.0 | 614.5 | 503.4 | 227.0 |  |
| 5 |  | 0 |  | 0 | 0 | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |  |
| 6 |  | 0 |  | 0 | 0 | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |  |
| 7 |  | 0 |  | 0 | 0 | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |  |
| 8 |  | 0 |  | 0 |  | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |  |
| 9 |  | 0 |  | 0 |  | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |  |
| 10 |  | 0 |  | 0 |  | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |  |
| 11 |  | 0 |  | 0 |  | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |  |
| 12 |  | 0 |  | 0 |  | 0 | 0 | 0 |  |  | 0.0 | 0.0 | 0.0 | 0.0 |  |
|  |  |  |  |  |  |  |  |  | 905 |  |  |  | 3166.7 | 6347.6 | kilopounds |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3159.0 |  |

Factor of Safety 1.00

Figure 10 Stability calculations for slope B-B' fully saturated, driven to failure.

## Discussion

The nearly equivalent range of internal friction angles, associated with failure for both the reconstructed slide area and the intact slope, suggests a similar degree of stability. With this in mind, the apparent lack of nearby landslides is slightly problematic, as any trigger would have affected the area equally. The slide complex is located at a change in slope aspect (direction of maximum gradient), where the apparent dip of the flow planes is greater than that of the nearby slopes. Thus, the landslide complex is located at a structurally less stable location, as confirmed by the stability calculations.

### *Interpretation of Qls1*

Qls 1 is a translational failure that is structurally controlled by flow planes and joint planes Figure 1. The slip surface of the landslide is parallel to the basalt flow planes indicating that Qls 1 likely failed along these flow planes that average 20 degrees of dip out of slope. The multiple small slides within Qls 1 suggest the deeper slide only partially redistributed energy. There was enough potential energy left in the slide mass to allow further landsliding. These multiple shallow slides indicate the slide material and the head scarp area remained unstable after the initial, deeper slide.

### *Interpretation of Qls2*

The steep topography and joint orientations along the margins suggests that Qls 2 is most likely a wedge failure. Wedge failures are a subgroup of translational slides that require intersecting fractures or joints that are planer or gently undulatory.[3] A wedge failure will not have any backwards tilting or rotary movement.[3] The eastern limit of Qls2 is well controlled by northeast trending north dipping joints and is somewhat controlled on its western edge by north-south trending east dipping joints. These joints meet at depth and intersect under the slide forming a wedge. The slide displays no rotary movement or backward tilting characteristics. Lateral ridges are present along the margins of slide Qls1 indicating Qls2 is the younger. The landslide had to have occurred after the basalt flow crystallized ~3.5 Ma. The sand filling the transverse cracks are probably from Pleistocene Harper Lake, which dried up ~ 25,000 years ago.[4] Therefore, the landslide occurred between 3.5 Ma and 25,000 years ago.

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