Colorado School of Mines

Highway 93 Slope Stability Analysis, Golden, CO

GEGN469 Project 1
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February 9, 2014

1.0 Introduction

The Colorado Department of Transportation (CDOT) has requested an assessment of the stability and potential mitigation of a landslide that developed on the east facing slope of State Highway 93, near Golden, Colorado (refer to Figure 1). The initial slope cut for the bypass was 35-ft-deep. Slow movement of the landslide began during construction and was then stabilized. In 1992, movement occurred again in the landslide, resulting in damages to the newly opened road. CDOT installed a drainage system to lower the high ground-water levels and re-graded the head scarp of the slide. Then, in 1993, a higher than normal amount of precipitation raised the ground-water levels and reactivated the landslide. Seeps and springs were flowing from the toe of the landslide and the tension crack at the head scarp was completely saturated by Magpie Creek at the time of failure. Approximately 500,000 cubic yards of material moved and closed the southbound lane of Highway 93. CDOT is currently considering additional mitigation alternatives to minimize the hazard to the road.

The purpose of this report is to provide a summary of the geologic and geotechnical models developed and discuss the sensitivity analysis and factor of safety evaluation of the landslide. Potential stabilization methods are also provided along with recommendations for mitigation. The scope of the project included the following:

- Development of conceptual geologic and geotechnical models
- Evaluation of the factor of safety against sliding for ground water conditions similar to those at the time of slope failure
- Sensitivity analyses of the factor of safety v. shear strength and ground-water levels
- Evaluation of potential stabilization methods of the slide

2.0 Background

2.1 Local Geology

There are three major faults that run through the Golden area. The three faults include the Golden Fault, Basin Margin Fault, and Clay Pits Fault which are illustrated at the end of this report in Figures 2 and 3 (Weimer et al., 2011). The Golden Fault zone directly impacts the landslide area.

The local geology in the slide area consists of quaternary alluvium, Pierre Shale, the Fountain Formation, and the Idaho Springs Formation (refer to Table 1 for material descriptions). The weathered portions of the Pierre Shale and Fountain Formation both are composed of soft, plastic clays that are highly weathered and weak materials.

Table 1. *Local Geology with Material Descriptions*

Unit Name	***Unit Description***	***Material Properties***
Alluvium	Silty gravelly sands. Loosely consolidated. Contains some cobbles and boulders	Wet Unit Weight (pcf)=120 Saturated Unit Weight (pcf)= 130 Cohesion (psf) = 0 Friction Angle (deg) = 25 Stabl5 Material Number = 1
Weathered Pierre Shale	Weathered claystones. Often tan or brown colored. Weak, soft and plastic.	Wet Unit Weight (pcf)=120 Saturated Unit Weight (pcf)= 130 Cohesion (psf) = 750 Friction Angle (deg) = 0 Stabl5 Material Number = 2
Pierre Shale	Shale- Black, hard, with near vertical bedding planes. Dry to moist.	Wet Unit Weight (pcf)=130 Saturated Unit Weight (pcf)= 130 Cohesion (psf) = 800 Friction Angle (deg) = 14.4 Stabl5 Material Number = 4
Weathered Fountain Formation	Sandstones and silty clayey sands. Maroon color. Weathered, micaceous, gravels in sandy silty matrix.	Wet Unit Weight (pcf)=120 Saturated Unit Weight (pcf)= 130 Cohesion (psf) = 750 Friction Angle (deg) = 0 Stabl5 Material Number = 3
Fountain Formation	Sandstone- maroon, coarse grained sand and pebbles, occasionally creamy-gray inclusions, some conglomerate. Wet to saturated.	Wet Unit Weight (pcf)=125 Saturated Unit Weight (pcf)= 135 Cohesion (psf) = 85550 Friction Angle (deg) = 30 Stabl5 Material Number = 5
Idaho Springs Formation	Mica Schist/Granite- gray-black, hard, some fractures, wet to saturated.	Wet Unit Weight (pcf)=125 Saturated Unit Weight (pcf)= 135 Cohesion (psf) = 85550 Friction Angle (deg) = 30 Stabl5 Material Number = 6

3.0 Geologic and Geotechnical Models

3.1 Geologic Cross-Sections

Using the boring logs collected by CDOT, cross sections were constructed in four locations across the landslide (refer to Plate 1 for cross section locations and to Plates 2-5 for individual cross sections). Boring logs from after the 1993 slide were primarily used to construct the cross sections. However, in some locations, boring logs prior to the 1993 slide were used to extrapolate geologic information due to the lack of post-slide boring logs.

The location of the slide plane was also interpreted using the boring logs. In general, the slide plane was located in the weakest materials including the weathered Pierre Shale and the weathered Fountain Formation. The water table was constructed using the water elevations a month after drilling in order to obtain static water conditions.

3.2 Geologic Isopach Maps

Isopach maps were developed using the thickness of material to the slide plane and the thickness of material above the groundwater table (refer to Plates 6 and 7). From the isopach maps, the deepest part of the landslide (greatest amount of material on top of the slide plane) is located in the middle of cross sections D-D’ and C-C’ (refer to Plates 4 and 5). The groundwater table is also deeper in the deepest part of the landslide, indicating that a larger volume of material is saturated in the middle of the slide than on the edges of the landslide (refer to Plate 7).

3.3 Geotechnical Models (SLIDE)

In order to evaluate the factor of safety against sliding for the ground-water conditions at the time of drilling, a computer modeling program called SLIDE was used to develop geotechnical models. Models for all four cross sections were developed by scanning in previously created cross-sections (Plates 2-5) into SLIDE. Scaling, material properties, groundwater tables and slide planes were implemented for each model. An evaluation of the factor of safety against sliding was completed using both Bishop simplified and Janbu simplified methods in SLIDE (refer to Figures 4-7). The following Bishop simplified factors of safety were determined for each cross sectional model at conditions close to those at the time of failure:

Table 2*. In-situ Factors of Safety*

Cross Section	**Factor of Safety**
A-A’	1.075
B-B’	1.007
C-C’	1.086
D-D’	1.041

*Note: Conditions close to the time of failure were assumed to have higher ground-water levels than at static conditions.

4.0 Sensitivity Analysis

Cross-sections B-B’ and C-C’ were selected as the most representative cross sections of the slide area. Sensitivity analyses, using SLIDE, were conducted for the factor of safety vs. ground-water levels and for the factor of safety vs. shear strength parameters (refer to Figures 8-10). Key shear strength parameters at the time of failure that were analyzed included cohesion, phi angle, and unit weight of the slide materials.

4.1 Factor of Safety v. Groundwater Table (refer to Figures 8 and 9)

The ground-water sensitivity analysis was performed by delineating a maximum and minimum water table. The factor of safety was computed for variations in the water table denoted as a percent variation from the mean water table. In both cross sections, the sensitivity of the factor of safety to changes in the groundwater level was significant with respect to raising the water table. When the water table was raised, the factor of safety decreased. When the groundwater level was lowered, the factor of safety increased. However the effect on factor of safety of de-watering more than several feet below the average water table was less significant than near and above the mean water table.

4.2 Factor of Safety v. Shear Strength (refer to Figure 10)

The material shear strength sensitivity analysis was performed by compiling the factor of safety against failure for each material's value of cohesion, friction angle, and unit weight using a +/- 10% variation in each parameter. For the cross section B-B', the following parameters of the materials shear strength greatly influenced the factor of safety:

***Table 3**. Shear Strength parameters for B-B'*

Unit	**Parameter**	**Factor of Safety**
Weathered Pierre	Decrease Cohesion	Decreases
Alluvium	Increase Unit Weight	Decreases
Alluvium	Decrease Phi Angle	Decreases

For the cross section C-C', the following parameters of the materials shear strength greatly influenced the factor of safety:

***Table 4**. Shear Strength parameters for C-C'*

Unit	**Parameter**	**Factor of Safety**
Weathered Pierre	Decrease Cohesion	Decreases
Weathered Fountain	Decrease Cohesion	Decreases
Alluvium	Increase Unit Weight	Decreases
Alluvium	Decrease Phi Angle	Decreases

5.0 Mitigation

Three mitigation options were investigated through modeling in SLIDE: 1) de-watering and unloading the head scarp, 2) de-watering and installing a support system, and 3) de-watering, buttressing, and unloading.

5.1 Option 1: Unloading Head Scarp & De-watering (refer to Figure 11)

Option 1 was analyzed in SLIDE by lowering the water table to near the slide plane which was approximately in the middle of the weathered Pierre and Fountain Formations. Material was also removed from near the head scarp in order to achieve a factor of safety of 1.5. In order to simplify calculations, the Fountain Formation was assumed to be within several feet of the surface just uphill of the head scarp. A total area of approximately 2,200 ft^2 was removed over the top 180 feet of cross section B-B'. Approximately 2,000 ft^2 was removed over the top 250 feet of cross section C-C'. The thickness removed from B-B' averaged 20 feet while from C-C' the cut depth averaged 16 feet.

5.2 Option 2: Supports & De-watering (refer to Figure 12)

Option 2 was analyzed in SLIDE by lowering the water table as described in Option 2 and using the back-analysis feature in SLIDE to determine the force necessary per-unit-width to increase the factor of safety to 1.5. In cross section B-B' a force of approximately 110,000 lbs per-foo- width was calculated and in C-C' a force of approximately 120,000 lbs per-foot-width was calculated.

5.3 Option 3: De-watering, Buttress, & Unloading Head Scarp (refer to Figures 13 and 14)

Option 3 was analyzed in SLIDE by lowering the water table as described in Option 1, removing an area of alluvium from the head scarp and creating a buttress of material at the toe of the slide with approximately the same cross sectional area as that removed from the head scarp. The buttress was assumed to have similar shear strength properties to a compacted alluvium with a cohesion of 800 psf and angle of internal friction equal to 15°. By removing material from the head and adding it to the toe, a total cross sectional removal of around 1,300 ft^2 for B-B' and 1,200 ft. for C-C' was determined. The buttress was keyed in 10 feet below the surface of the toe and extended 50 feet back into the slide. The height of the buttress was 30 ft. in B-B' and 20 ft. in C-C'.

6.0 Conclusions

Through the analysis of the geotechnical models and several possible mitigation options, several conclusions are drawn:

- The factor of safety is most sensitive to variations in cohesion of the weathered Pierre and Fountain Formation as well as the unit weight of the alluvium material in the slide. These parameters contribute to the overall shear strength of the slide material.
- The factor of safety is also sensitive to changes in the groundwater table. Notably, if the water level is raised, the factor of safety decreases, especially in cross section B-B'.
- De-watering is an important component of stabilization, however, on its own cannot sufficiently raise the factor of safety and thus should be pursued in combination with other mitigation schemes.
- Removal of material from near the head scarp is a viable way to increase the factor of safety by unloading the slide.
- Nearly equivalent volumes of alluvium could be removed from near the head scarp and compacted into a toe buttress in order to efficiently raise the factor of safety.
- Although detailed analysis of tie backs and other supports was not conducted, a force necessary per-unit-width of the slide in the B-B' and C-C' areas was computed to achieve a factor of safety of 1.5 and could be used in feasibility studies for future mitigation.
- Shear strength parameters are the most sensitive in terms of their effect on the factor of safety. Better characterization of the shear strength parameters of the alluvium and weathered Pierre Shale is needed in order to further constrain the strength parameters of these units.

7.0 Recommendations

This report has provided initial analyses of the landslide and several mitigation options. Recommendations for future steps include:

- Perform detailed studies comparing the feasibility of unloading and buttressing vs. installing support systems (tie-backs, MSE walls, etc.) or a combination of the two.
- Perform feasibility studies comparing methods of de-watering the slide (ex., passive vs. active).
- Additional borings on the upper part of B-B' and the lower section of C-C' would aid in delineating the slip plane and material contacts in this area. This would further constrain the model and provide a more accurate factor of safety.

References

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