Slope liquefaction failure of a rip-rap slope during springtime in a northern climate

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A common problem in northern climates during the spring is slope failures occurring on slopes constructed the previous year. The main cause of the failure is a lack of vegetation coupled with ground freezing that prevents water drainage. Typical remediation of failed slopes is to reconstruct the slope back to its original configuration and place rip-rap over the failed section of the slope; a remediation technique that has been found to work well. This case study discusses the construction of a slope adjacent a state highway that utilized a geotextile separator and rip-rap in the construction of the slope. The following spring, however, the slope dramatically failed resulting in a large amount of soil flowing onto the state highway and a sinkhole forming on the back side of the slope. The primary cause of failure was found to be clogging of the geotextile thus allowing snowmelt and rain to generate pore water pressures behind the geotextile in excess of the rip-rap's ability to prevent failure.

INTRODUCTION

Geotextiles play an important role in geotechnical projects. A common use is as a separator and filter in drainage and erosion control applications (Holtz 2002). In a temporary erosion control application geotextile, such as silt fencing, the geotextile is placed along slopes to prevent soil erosion by containing the soil and turbid water in a one-time operation. In a permanent erosion control application, however, the geotextile must be designed for the long term. While most applications of geotextiles are successful, there are a number of case histories where geotextiles had inadequate performance. Koerner and Koerner (2015) reviewed 69 cases of geotextile failures where the term failure was used to describe unsatisfactory performance of the geotextile filter or the associated drainage system. They reviewed the sources of failures in these cases and attributed them to design, atypical soil type, and unusual permeant and installation issues.

This study presents a case study in which a road was constructed through a glacial soil slope to access Michigan State Highway M-203. The site is located adjacent the Portage Lake Waterway north of Hancock, Michigan on the Keweenaw Peninsula in Michigan's Upper Peninsula (UP), as shown in Figure 1. While most cut slopes in the local area are generally seeded or mulched after construction, in this case the slope was lined with a geotextile and rip-rap placed over the geotextile as protection against failure due to its location adjacent a state highway. The slope, however, dramatically failed in the spring following construction the previous summer. The purpose of this paper is discuss the causes of the slope failure including an investigation of similar slopes in the area. This is followed by a review of the area's geology, the site soils and geotextile used in the construction of the slope. Finally, an assessment as to the cause of the slope failure is presented.

Figure 1: Site location map

REVIEW OF LOCAL SLOPE CONSTRUCTION AND FAILURES

In northern Michigan it is common to have some limited landslides develop on newly constructed slopes the following spring due to a combination of freezing temperatures and high snowfall. Figure 2 illustrates two small-scale landslides near the site area that failed in the spring of 2016. The first slide (Figure 2 a and b) was constructed in the fall 2015 on a roughly 2:1 slope (27°) and sodded to prevent spring time erosion but had a small "pop out" the following spring. Figure 2 c and d, however, show a larger landslide on an established slope that was at least 30 years old that also occurred during the spring 2016.

One issue in the design of slopes in the site area is that the soils were deposited by glaciers. This can be seen in Figure 2 (c) and Figure 2 (d) showing a wide range of particle sizes including well-rounded cobbles and boulders. Overall, a large percent of the glacial soils tends to be coarse-grained with cobbles and boulders and a relatively high fine contents. Being geologically recent deposited soils, the sand and silt portions are relatively angular with corresponding high friction angles, although as seen in Figure 2c and 2d the cobbles and boulders are highly rounded due to glacial action.

Figure 3 shows a commercial site where the slopes were excavated to an average slope of about 35° with some portions as steep as 40°. The slope remained stable for a number of years until fifteen years ago a portion of the slope failed. This failure was remediated with rip-rap and has remained stable since. A recent winter, however, with relatively high snowfall but with record low temperatures caused the slopes on each side of the remediated area to fail, while the rip-rapped section remained stable. These later failures have not been remediated but have remained more or less stable. Figure 4 is a recent photograph of vegetation developing on the commercial site shown in Figure 3.

Figure 2. Spring, 2016 small scale landslides in the Hancock-Houghton area: (a) slope constructed in fall 2015 and sodded, (b) spring 2016 small scale failure on slope; (c) small landslide on an established slope, (d) soil flowing behind a commercial building.

Construction on slopes as steep as 35° to 40° is difficult. Most steep slopes are constructed with bulldozers and depending on the type and make of the dozer they are generally limited to 40° slopes, e.g., a John Deer 450J dozer (John Deere 2016). On steep slope construction the general method is to push the soil downslope as seen by the dozer tracks in Figure 2(a). One problem with this method in glacial soils, however, is that it is common to encounter small deposits of silt or clay in the slope. As the dozer pushes past these deposits, the soils are spread along the slope creating lower permeability zones on the slope's surface. Further, in the spring, snowmelt and rainwater draining through the soils encounter the low permeable layers (typically horizontal silt and clay layers) in which the water "ponds" on these layer forcing the water to move laterally to the slope. However, the water encounters the low permeability layers along the slope building up pore pressure behind the slope and in some cases resulting in slope failure. Based on numerous observations it appears that after the vegetation has been established on the slope or rip-rap placed on the slope, the slopes tend to be stable over time with exception of extreme winter conditions in which spring landslides become more common.

Figure 3: Commercial site with excavated slopes in the range of 30° to 40° that experienced three slope failures. The middle section of the slope, which failed first, was remediated with rock rip-rap, while the slope failures on either side have not been remediated

In general, with high snowfall amounts, the snow tends to act as an insulator and prevent deep ground freezing on many slopes. In years with early snowfall, it is common that the ground, while initially freezing, can also thaw soon after snowfall and remain unfrozen throughout the winter. In areas where the snow is low or removed, however, such as on roads and wind swept slopes, deep freezing does occur. Therefore, due to the variations in temperature and snowfall, it is also possible for ground freezing to be variable in depth and extension; freezing one year and not another.

Figure 4. Recent photograph of the commercial site shown in Figure 2 with vegetation developing on the slope.

M-203 SLOPE FAILURE

As noted above, the failed slope is located in Michigan's Upper Peninsula (Figure 1). Due to its location near Lake Superior, the area receives a large amount of lake-effect snow, averaging about five meters per year. Temperatures in the summer average a high of 23.9° C and in the winter a low of -12.8° C (US Climate Data 2016). The area averages about six months of freezing weather between December and March.

To gain access to Michigan State Route M-203 the road was constructed through a 30 ft (roughly 10 m) high glacial slope as shown in Figure 5 (a). The slopes were cut to a 2:1 angle (27°). Although a 2:1 slope is generally considered stable in the local area, a thin woven geotextile layer was placed on the slope and rip-rap placed on top of the geotextile in the summer of 2013 to protect the slope from erosion. In the spring 2014 the north facing slope failed causing a large amount of sand to flow out onto M-203 to a depth of 0.25 m, and forming a sinkhole behind the slope. The site was quickly repaired to allow traffic to use the highway. Unfortunately, no pictures were available to show this failure. Later that summer the slope was reconstructed with a new ditch, separation fabric (woven slit film geotextile similar to a silt fence material) and rip-rap. Figure 5(a) and (b) illustrates the road and slope after it was remediated in 2014. Figure 5(a) shows a green erosion control blanket where the sinkhole formed in back of the slope. In the spring of 2015 a much smaller failure occurred with sand and water again flowing out of the slope as seen in Figure 5(c). The site was cleaned up and minor modifications made to the slope. Figure 5(c) shows the site a few months after remediation with some water and sand still flowing out of the slope. Figure 5(d) shows the geotextile fabric placed below the rip-rap. Also, no soil blanket was placed over the geotextile fabric for cushioning the placement of the rip-rap, thus damage to the geotextile also occurred during placement of the rip-rap.

Figure 5. Road accessing M-203 with springtime failure: (a) road after the first failure and remediation, (b) silt fence containing additional sand and water still flowing from the slope, (c) 2014 second failure after remeidation, (d) geotextile directly under the rip-rap on the slope.

SITE GEOLOGY AND SOILS

The general area consists of glacial end moraine, which according to USDA-NRCS (2016) are "*dissected ground moraine characterized by a dendritic pattern of hilly to very steep ridges and ravines. Ephemeral streams are common. This landform consists of till and glaciolacustrine deposits. In some places sandy outwash soils are a component of this landform due to the proximity of the rapidly melting glacier and the influence of glacial lakes. Sandy and silty stratified soils are common in some places while coarse-loamy till is dominant in others*." Hughes (1963) conducted a field study of a six quadrangle area that included the study site. Based on Hughes's field map the site is located between two ground moraines, the Portage and High Point Moraines, consisting of sandy outwash with some limited gravels and cobbles. The groundwater table was estimated to be approximately 2 to 4 meters below the slope based on nearby water well records and the elevation of the Portage Lake Waterway.

The slope soils consists primarily of stratified light brown sand and silt (glaciolacustrine), classified as a SM soil with fines averaging 8 to 15% [ASTM D1140-14(ASTM 2014)] with some limited gravel and cobbles. Figure 6 provides the mechanical grain size analysis on dry soils for three grab samples taken from the excavated soil (soil 2 to soil 4). Due to a larger amount of fines affixed to the larger size particles the fine content (>0.075 mm) shown in Figure 6 is lower than the washed fines analysis indicated above. The average coefficient of uniformity and coefficient of curvature is C_u = 10 and C_c = 3.3 for the four samples tested from the site based on the "dry sieve" analysis.

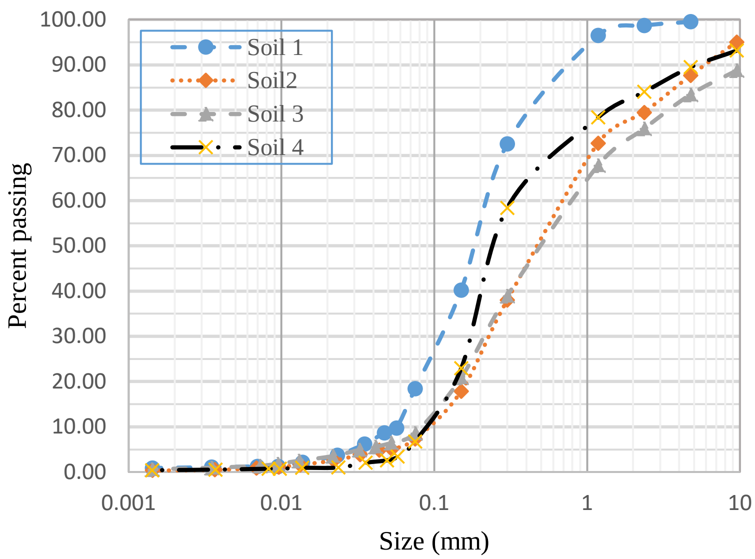

Figure 6. Grain size distribution of the soil samples

According to Luettich et al. (1992) soils with coefficient of curvature (C_c) greater than three or smaller than one have a higher probability of being internally unstable. Kenney and Lau (1985) also noted that grading instability is likely to occur in soils that have gently inclined sections (wide range of particle sizes) in the lower section of their grading curves. As such, Figure 6 would suggest that the site soils have a high probability of being internally unstable.

Direct shear tests on the soil samples from the area resulted in an average friction angle of 41°. While this is a relatively high friction angle, it is consistent with tests on sands from a local sand and gravel quarry located on M-203 in the similar glacial soils.

EROSION CONTROL GEOTEXTILE

The geotextile used on the slope was a woven slit film geotextile. It appears that the main goal of using geotextile on the slope was as a separator between the soil and the rip-rap to control erosion with limited consideration for the filtration ability of the geotextile. For filtration, the geotextile must be permeable enough to allow a relatively free flow through it, while retaining the soil large particles to allow soil filter bridge form over the geotextile holes. Further, the majority of the openings in geotextile must be sufficiently larger than the smaller particles of the soil, so the geotextile will not clog or blind (Christopher and Fischer 1992). In case of poor filtration ability of the geotextile, groundwater cannot escape through the geotextile. This results in pore water pressure buildup behind the geotextile called ballooning (Design Manual M 22-01.13, 2016)

SIMPLIFIED FILTRATION AND CLOGGING TESTS

To assess the "filtration" capacity of geotextile used on the slope a simplified filtration and clogging test was conducted. The geotextile fabric used on the slope was a woven monofilament fabric commonly similar to fabrics used for silt fence control. To test the geotextile's filtration and clogging capacity one side of a plastic container was cut out and the fabric placed and secured in the bucket as shown in Figure 7. The container was first filled with water to test the filtration capacity of the geotextile. After observing a relatively good water flow through the geotextile, five-gallon buckets were filled with soil and water creating sand/water slurry. The buckets were then filled with the sand/water slurry to a height above the fabric. Water, free of observable sediments, flowed from the fabric in a similar rate as with just water behind the fabric. During the test, water was added to the container to maintain a constant slurry height. The fabric functioned well, retaining the sand particles and allowing the water to pass and as shown in Figure 7. After completing the test, the buckets were emptied and the backside of the fabric washed with water. The test was then repeated filling the bucket with the sand/water slurry. On the second filling, however, the fabric failed to function properly not allowing water to filtrate through the fabric. The test was repeated a number of times without washing the fabric off and again with washing the fabric. In all cases, the fabric failed to function the second time the sand/water slurry was placed in the bucket. Inspecting the fabric, it was seen the much of the available openings were clogged with sediment, thus not allowing water to flow through the fabric.

Figure 7. Woven slit film geotextile simplified filtration test

DISCUSSION

Slopes constructed in the local area range from 27° to 40°. Due to high friction strength of the soils these slopes tend to be stable over time, with the exception of limited slope failures in the spring after initial construction or after an extreme winter with either higher than usual snowfall or deep freezing. In general, the flatter slopes, such as 27° or less, are considered safe and as a rule rip-rap is not utilized. In this case study, however, the slope was adjacent a state highway and therefore the contractor decided on protecting the slope with a rip-rap along with a geotextile separator to prevent erosion from the slope onto the highway. In cases where the design is left to a contractor it is a common practice to use a “fabric” on the slope. While the issue of separation is clearly understood, the issue of filtration tends not to be. It was therefore a surprise to the contractor (and site owner) the following spring that such a dramatic slope failure would occur without having had an extreme winter. The obvious cause of the failure was a buildup of pore water pressure behind the geotextile.

The slope was constructed in the summer. Since the groundwater table was below the slope, it did not contribute water flow into the slope. However, in the fall, rain and snowmelt would have flowed over and through the geotextile carrying some amount of sediment. This situation is shown in Figure 8. It is believed that at this point the geotextile developed some level of clogging but probably not sufficient to prevent water flow through the geotextile. In the spring, however, the snowmelt would have contributed significantly to groundwater flow.

Topographically, the slope was constructed at the base of a 100 m (300 ft) high hill and would have had significant groundwater moving through the soils. Seeps are common along this section of highway suggesting the presence of localized silt or clay layers in the soil. These layers in turn would pond the ground water causing the water to flow laterally towards the slope as illustrated in Figure 8. Further, the soils having the higher probability of being internally unstable, typical of glacial soils, would have caused particle migration into the geotextile, resulting in a more complete clogging of the geotextile. Once the geotextile was clogged pore water pressure developed causing the dramatic slope failure and soil liquefaction flow onto the state highway. If the geotextile had been designed for filtration it is likely that this slope would not have failed. Moreover, if the slope had simply been lined with the rip–rap, it is likely that water flow from the spring meltwater would have been able to exit the slope without building pore water pressure in the slope. In effect, it is believed that the geotextile, once clogged, acted as a barrier to the spring groundwater flow leading to the failure.

While it is well known that a thin woven geotextile would function reasonable well as a separator, at least until the slope developed sufficient vegetation either on its own or between the rip-rap over time, its ability to also function as a "filtration" layer is commonly not considered on these types of small projects. The filtration experiment presented in this paper, while being a crude form of a filtration test, demonstrated that the geotextile used on the slope functioned well as a silt fence, preventing slope soils from eroding onto to the highway from beneath the rip-rap. A key point demonstrated in the experimental tests, however, is that once the geotextile functions as a silt fence its ability to provide filtration is compromised.

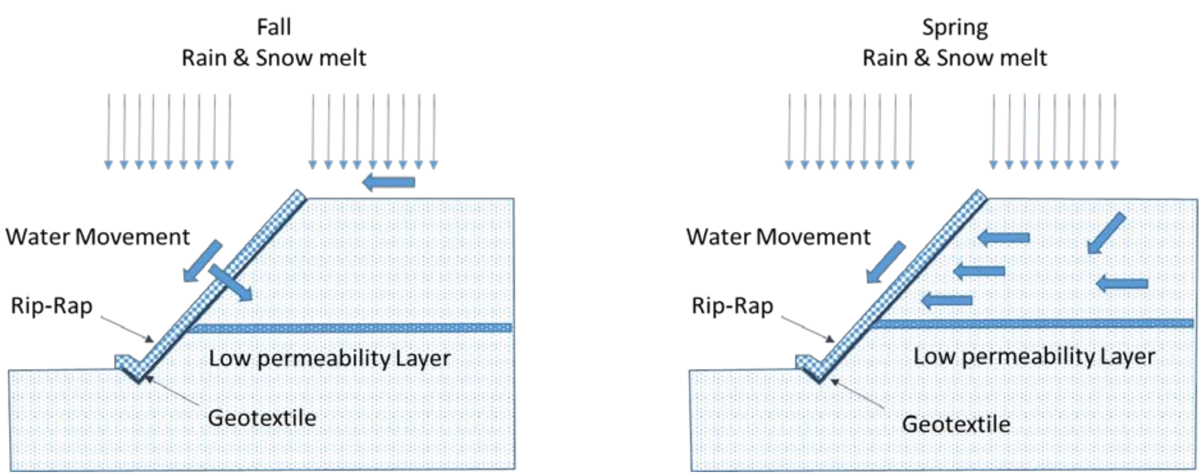

Figure 8 Schematic drawing of the slope's water movement in the fall and spring.

CONCLUSION

While natural slopes in the local area are stable up to slope angles of 35° to 40°, constructed slopes at those angles can be problematic and prone to slope failure due primarily in the spring from heavy snow winters and rapid snowmelt. As a general rule, slopes constructed at a 2:1 tend to be stable although small scale slumps can occur while armoring slopes with rip-rap appears to be effective. Another issue was that no cushioning sand layer was used beneath the rip-rap (see Figure 5 d). A piece of exposed geotextile taken from the slope is shown in Figure 9 where a large hole formed due to the rip-rap being dropped onto the geotextile can be seen.

Figure 9. Large hole in the geotextile due to improper geotextile installation

This case study showed an inappropriate design and installation of a woven geotextile that caused slope failure. The geotextile was not designed for filtration and had been installed without proper bedding soils. Therefore, it was clogged and resulted in pore water pressures developing behind the slope. The pore water pressure in silty sand in slope causing soil liquefaction resulting in the flow of water unto a highway and a sinkhole developing on the backside of the slope.

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