Luc Burnier, Julia Bailey-Wells, Ben Gaucherin, Derek Marquis

Paul Bierman

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Strategies for Mitigating Landslides: A Case Study on Riverside Ave Burlington, Vermont

Abstract

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Landslides have had detrimental effects on many places around the globe. Due to the impacts of Climate Change, more extreme weather events will occur resulting in an increase in precipitation, which can cause more landslides to occur. Human development and land-use change can also increase the likelihood of landslide occurrences due to an increase in runoff as well as causing soil instability. This paper will discuss the reasonings behind why landslides occur, specifically looking at the hillslope along Riverside Avenue in Burlington, Vermont. Topics that will be covered include: whether these landslides are natural or human induced, the role of surface and ground water hydrology on the landslides, the glacial history of Riverside Ave, and lastly the mitigation strategies needed to reduce landslides at Riverside Ave and other areas prone to landslides.

(Main paper word count: 1894)

Introduction

Many landslides have occurred along Riverside Ave over the past century. There are many reasons for why these landslides have occurred, the most notable being fill being placed in Riverside Ave. Much of that fill is still present, where during landslides that occurred in 1955 wooden cribbing was used and then sand was poured to create to stabilize the slope. Later rocks were placed on top of the fill and then that area was later paved to rebuild the street. Later landslides continually happened on Riverside Ave likely due to poor maintenance that was set-in place (Bierman et al., 2005). The 2019 Halloween slide likely occurred due to the over saturation of the soil due to heavy precipitation. The steepness of the slope and thick slab material such as parking lots, buildings, vehicles, and other impervious surfaces was likely a contributing factor to why the landslide occurred. Aerial and ground level photos show that prior to when the 2019 landslide occurred, there are major indications of stress on the slope. There weren't that many trees present on the slope and the ones that were on the slope showed signs of pistol butting.

Most of the vegetation before the 2019 landslide consisted of small vegetation like grass and shrubs with a few trees. The lack of strong tree root cohesion likely was a contributing factor to the landslide. Major amounts of run-off likely occurred because the majority of surfaces above the slope were and still are pavement and hard compact gravel. Almost all of the landslides that happened did occur at the same location as the 1928 landslide; located on the edge of a major ravine shown clearly in Figure 1. More landslides happened in 1955, 1959, 1968, 1972, 1976, 1981, 2000, and most recently in 2019. Human presence is also a major factor for why many landslides have occurred. Throughout the 20th century more housing, commercial buildings, and impervious surfaces like paved roads and parking lots have caused more shear stress on Riverside Ave hillslope.

The distribution of landslides along Riverside Ave are the result of differences in the topography. More specifically, the distribution relies on pockets of low shear stress thresholds, poor soil cohesion due to lack of vegetation, and areas where the water table could condense runoff. The interplay of these main topographical characteristics is what determines how likely areas are to surpass their thresholds for sliding when acted upon by forces like heavy rain, weight bearing, and weathering. As can be seen in Figure 1, certain areas exhibit a colluvial fan pattern in which steep walls splay out into more gently sloped fans. These areas are hotspots where sliding is more likely to happen. The distribution of these hotspots happen naturally, but further along this paper will address the role of human intervention in accelerating, decelerating, and moving these hotspots.

Figure 1:
1872 map overlaid with a 2014 hillshade derived from LiDAR.

Figure 2:
Panorama of where the 2019 landslide had occurred was taken roughly a year later. It's worth noting that a lot of vegetation has regrown, however, no maintenance has been put into place except for some riprap stones at the very top of where the parking lot meets the edge.
Photo Credit: Luc Burnier

Background on Landslides

Landslides occur in nature without human influence. Depending on where you are, landslide dynamics on hillslopes can differ based on climate, vegetation, substrate, and sediment characteristics. In general, landslides are based on a type of sediment transport called *mass wasting*, which is the movement of sediment from higher to lower elevations along a hillslope occurring from the gravitational stress exceeding the slope's material resistance.

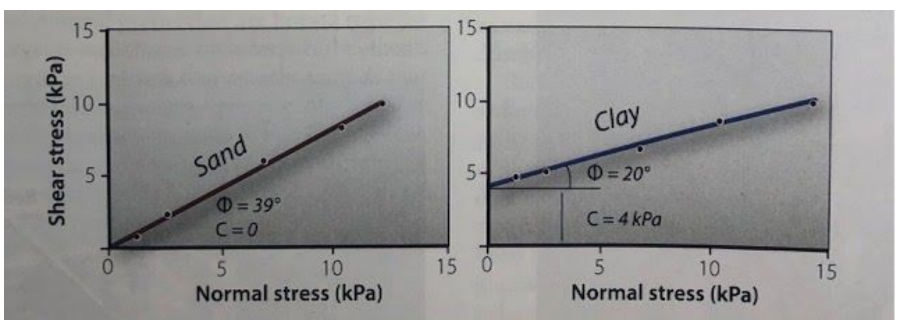

Figure 3:

(Bierman and Montgomery 2020)- The relationship between normal stress and shear stress on sand-based vs. clay-based hillslopes; clay has the higher y-intercept value due to its cohesive properties and its resisting force on shear stress.

On a hillslope, there is a relationship between driving forces and resisting forces. The sliding of one body of sediment over another is known as *shearing stress*, and the ability of a sediment load on a hillslope to resist this stress is known as *shear strength*. This shear strength acts as the main resistance force against gravity, which is the main driving force. The strength of cohesion within soil, the amount of vegetation, and the *angle of internal friction* (angle of slope) impact the likelihood of slide occurrence. *Cohesion*-which is the tendency of materials, like sediment, to stick to itself-and friction make up what is shear strength. More porous soils, such as those with higher sand content, have lower cohesion compared to less porous soils that contain more silt and clay and thus are more prone to sliding (Figure 3).

Vegetation, particularly those with developed root structures, supply structure to soil and can make hillslope more resistant to slides. Steeper slopes reduce impact on resistance of *effective normal stress*, which is the perpendicular force of the sediment load's weight on the hillslope. In addition to these hillslope characteristics, heavy rainfall in a short period of time can be the tipping point for slides to occur, as this influx of water fills the pore spaces in the soil and pushes the vulnerable sediment away from the direction of the normal stress; this is called *pore pressure* and it reduces normal stress, making conditions more conducive for sliding. Over time, various biotic and abiotic factors in ecosystems can contribute to the structure changes that hillslopes go through which make more or less vulnerable to sliding.

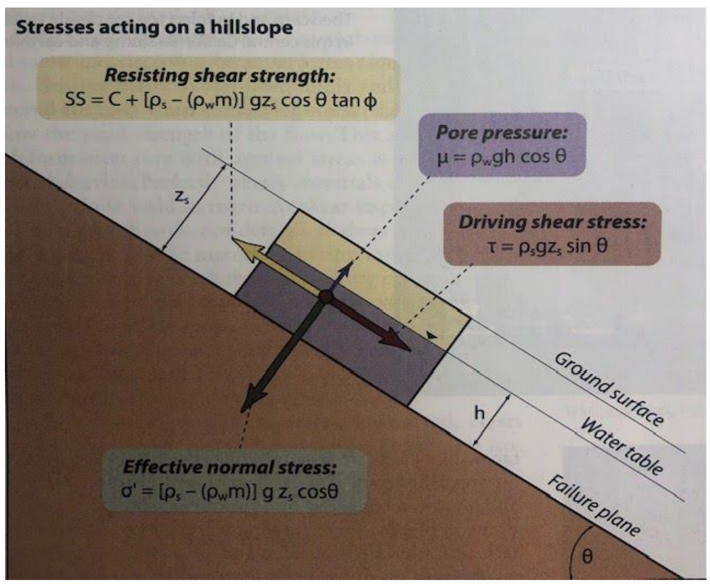

Figure 4:

(Bierman and Montgomery 2020)- The directional forcings and relationships between shear stress, shear strength, pore pressure, and effective normal stress.

Humans can also increase the likelihood of sliding on hillslopes. Changes in land-use like deforestation, urbanization, and hilltop dumping/fill can influence sliding occurrence. The removal of vegetation makes soil weaker due to the lack of root systems supplying structure. This removal of vegetation, as well as the presence of impermeable surfaces in developed areas (like asphalt and concrete), increases runoff intensity shortly after a rain event; this can lead to soil instability and higher poor pressure acting on sediment loads that are vulnerable to sliding. Dumping and filling of various materials adds matter to the upper area of the hillslope, therefore increasing the slope and angle of internal friction. The steeper the slope/higher the angle, the closer the direction of the shear stress gets to the direction of gravity, thus reducing the normal stress and making conditions vulnerable to sliding. Ultimately, humans play a role in both creating landslides and making natural landslides more likely.

Riverside Avenue runs parallel to the Winooski River, a factor which plays heavily into the area’s instability. An 1872 map shows a narrow stream running from the South to the North side of the road down to the river. In combination with the steep slope of the hill, the moving water in this stream encouraged erosion. Soils in the Burlington/Winooski area are mostly deposited glacial sediment left by the retreating Laurentide ice sheet, which is in large part low-cohesion till. The loose nature of the Riverside hill soil only encouraged both gravity and infiltration-based erosion, especially when combined with the loose sand and gravel placed there in attempts to stabilize the slope starting in the 1930s. In the area’s 1955 slide, water from an unused culvert further eroded the road foundation, causing the slope to cascade into the river below. Though the landslide-prone nature of the area is in part due to the dumping outlined above, most slides were triggered by precipitation events, which both led to heavy natural runoff and led to flooding of sewage and pipe systems.

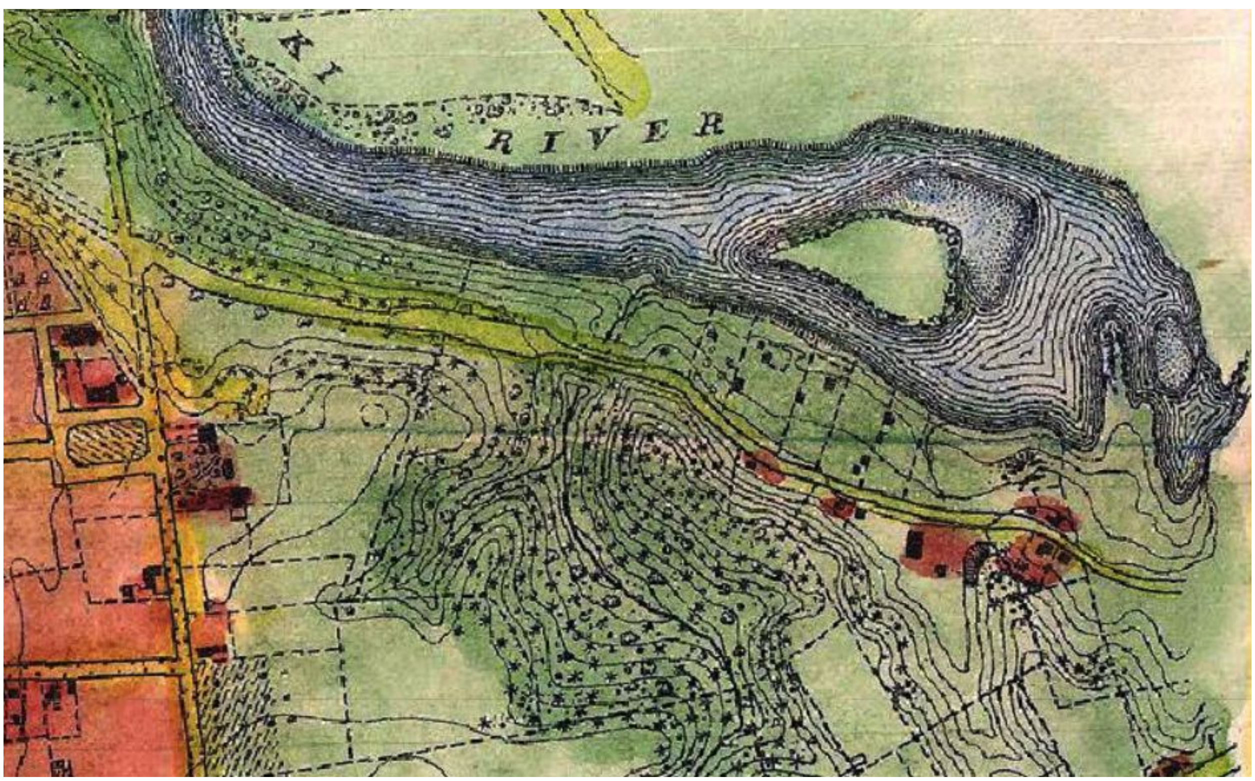

Figure 5:
1872 Geological Survey map of Riverside Ave.

Landslide Mitigation for the Future

There are many steps that need to be taken in order to minimize the occurrence of landslides in the future.Over the years, maintenance crews have done a relatively poor job in constructing effective slope stabilizers. Whether this has to with a lack of funding remains unclear, however, there are many ways in building effective slope stabilization techniques. One technique for reducing the risk of future landslides could be improving surface and subsurface drainage systems. The overflow of runoff is a large factor for landslides and improving these systems can stabilize a landslide-prone slope. In order for this to work, a drainage channel needs to be put into place to divert the surface water away from the landslide region. This will make sure that water doesn't accumulate near the landslide prone area (Kansas Geological Survey, 1999). Another technique is removing the soil and rock at the head of the where the landslides occur so that the driving pressure is reduced. In the case of Riverside Ave, this wouldn't be an adequate technique because the businesses, housing, parking lots, and roadways that are all resting on the flat before the slope pitches. Buttressing the toe is another technique where fill is added at the toe (bottom) of the hillslope so there are resisting forces to stop landslide debris. Creating some sort of barrier at the bottom of the hillslope would also prevent any soil from leaching into potential nearby water bodies like the Winooski River. Preserving vegetation on landslide hillslopes can also have a huge impact on increasing soil cohesion due to root structure holding the soil, but also reduce the amount of water that percolates through the soil causing erosion to occur. Reinforced soil structures like geogrids can be effective slope stabilizers. Geogrids are constructed by placing alternative layers of metal reinforcement and compacted soil to create a structure hindering lateral forces (Mandavkar and Weldu, 2019). Ancient soil-reinforcement used any materials like tree branches and straw, however, modern reinforcement elements include steel grids, wire meshes, or geotextile sheets. The image below showcases what a geogrid looks like followed by a diagram explaining how it functions:

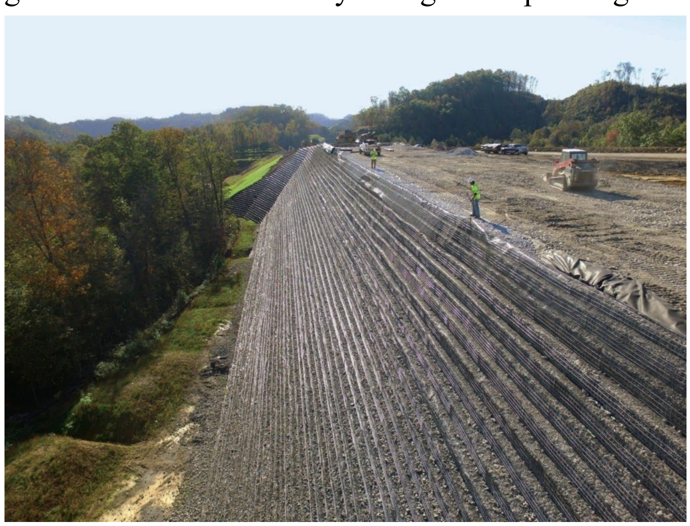

Figure 6:
A reinforced soil structure being constructed.
Source: (Mandavkar and Weldu, 2019)

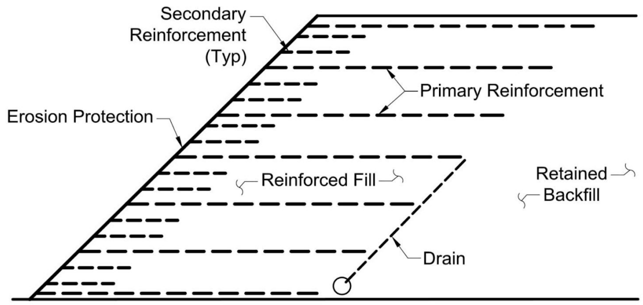

Figure 7:
Diagram showing how a reinforced soil structure functions.
Source: (Mandavkar and Weldu, 2019)

There are many economic and social consequences to landslides. that when reducing the risk of future slides can create major potential savings for towns and cities budgets. There are many long term economic benefits for mitigating future landslides. A case study in Contra Costa County, California was done to see whether state-of-the-art mitigation strategies were put into place in minimizing potential landslide hazards and what would the outcome of savings be. A 90 percent reduction in spending was shown with a cost-benefit ratio of 8.7:1, meaning that for every $1 that was spent, $8.70 was saved (Wold, Jr., Robert L., Jochim, Candace L., 1989). It was noted in this study, that around 80 percent of landslides that took place were because of human activity. Similar studies like cost benefit analyses should be done on Riverside Ave in order to determine the best possible outcomes the area can have both economically and environmentally if state-of-art mitigation strategies were used.

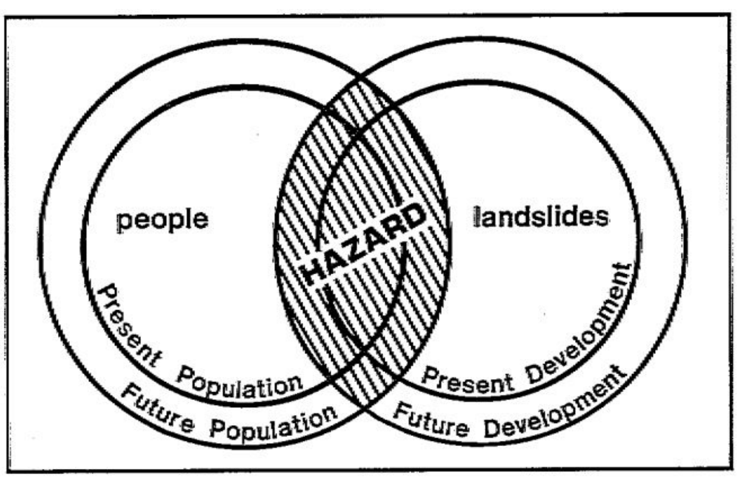

Figure 8:
Venn diagram showing how present and future population of people is linked to increased landslide occurrence
Source: (Wold, Jr., Robert L., Jochim, Candace L., 1989)

Conclusion

There's a lot of relation here with what's happening at Riverside Ave due to the high presence of human activities. Many residents who live on Riverside Ave are adamant on staying as well as businesses like restaurants, gas stations, and auto-repair shops. Ultimately what it comes down to is how will the city of Burlington decide what mitigation strategies will be the most effective in reducing areas prone to landslides. Informing the public not only the economic and social consequences but also the wildlife that's distrubed when these landslides occur is crucial. Landslides have caused much harm in terms of pollution of phosphorus leaching into nearby water bodies. Riverside Ave is located along the Winooski River eventually leading to Lake Champlain and phosphorus leaching into water bodies has had a major detrimental effect on water quality. A possible step forward to making sure that city officials and road maintenance crews is being able to communicate with road crews on what best management practices will be the most cost effective as well as the most durable in the future. It's important to understand that major weather events will occur in the future and that better hillslope infrastructure needs to be implemented. Figuring out the best ways to educate people whether it be road crews or city officials on thinking about long-term rather than short-term strategies for climate adaptability in mitigating future landslides.

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