Riverside Avenue Landslides: Landscape Change and Slope Instability

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Abstract **(171 words)**

The purpose of this paper is to evaluate both the human and natural causes of Riverside Avenue landslides, and to find possible ways to prevent them in the future. The study area is under specific concern due to human impact and the repeated failure of these slopes. Human impacts include construction, development, and reconstruction of Riverside Avenue, thus increasing the load on top of the slope and overall runoff to the slopes. This study looks at the science behind slope morphology and hydrology, as well as historical records that document landscape change around Riverside Avenue over time. We reviewed a variety of data including historical news clippings, photos, and data on previous landslides. The conclusion of this study is that Riverside Avenue landslide triggers are natural yet anthropogenically exacerbated; preventative steps are needed to stabilize these previously failed slopes. Remediation could include restoration of soil material and planting of vegetation, as well as de-urbanization in the area as the slopes have proven to fail under the heightened stresses from human activity.

Landslide Mechanisms and Triggers **(1099 words)**

Landslides are earth hazards that have multiple possible triggers. When the driving shear stress exceeds the resisting shear stress, the slope becomes unstable, resulting in material carried down slope (Fig. 1). Slope instability can be triggered by decreasing soil cohesion, excessive and sudden influx of water, and gravity's force over time. Soil cohesion is compromised by deforestation, excessive filling, and compaction of material. The removal of vegetation causes a decrease in soil cohesion, because root systems play an integral role in maintaining slope stability. Heavy rainfall and excessive snowmelt causes a flux in discharge runoff, thus increasing porosity and the likelihood of slope failure. The primary driving force for landslides to occur is gravity; gravitational force pulls material downslope at varying rates depending on a variety of factors, such as soil cohesion, slope angle, and the magnitude of the normal stress (Fig. 1). Soil creep is the slow, episodic movement of material downslope due to gravity. Leaning trees and pistol-butt trunks on the banks near Riverside Ave. is an example of consistent, gradual, downslope movement, which is evidence of an unstable slope (Fig 2).

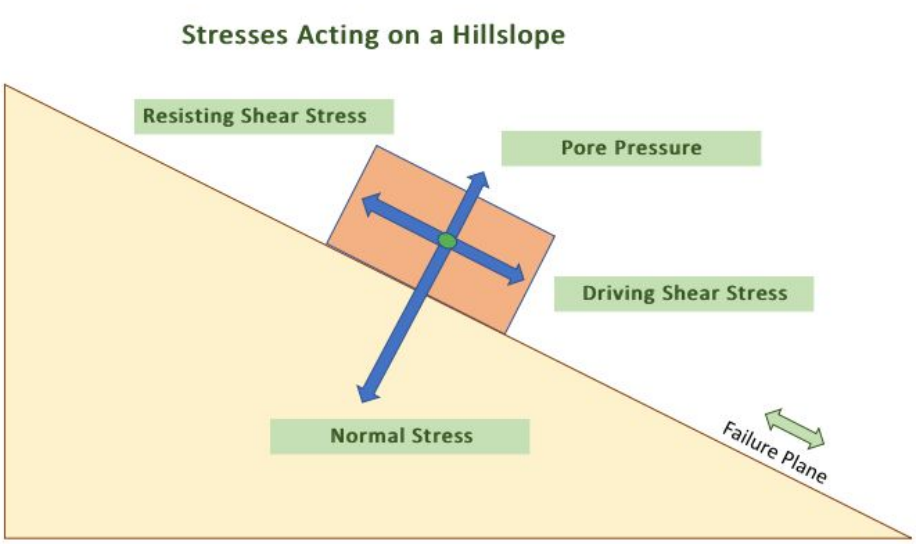

Figure 2.
Photographs (R. Farrell) of the slopes near Riverside Ave, illustrating evidence of pistol-butt trunks (blue box) and tilting trees (red box). This slope angle is approximately 30º

Figure 1.
The figure above depicts the relationship between resisting shear stress, driving shear stress, pore pressure, and normal stress. These active stresses and their relationship with one another determine the likelihood of a landslide occurring. (Figure done by Leah Sutphen).

Riverside Ave. Landslide Background and Spatial Distribution

Landslides are naturally occurring events that can be instigated and exacerbated by human activity. With that being said, nature typically does an effective job at stabilizing the slopes, whereas historically human development has had drastic impacts on the destabilization of slopes. Land-use changes have had a significant effect on the spatial distribution of landslides. The development of Riverside Avenue has led to an increase in landslides, due to the increase in impermeable surfaces and soil compaction.

The geomorphic and glacial history of Riverside Avenue also plays a significant role in explaining the frequency of landslides. The advance and retreat of the Laurentide ice sheet caused most of the soil to consist of sandy till, which is low in cohesion, as well as glacial clay. While the presence of vegetation made up for that lack of cohesion, human deforestation has undone that effect. Slope angle is a significant factor in slope stability: the steeper the slope angle, the greater the driving force, and higher likelihood of a landslide. The slope angle of the banks north of Riverside Avenue is around 30º (Fig. 3.)

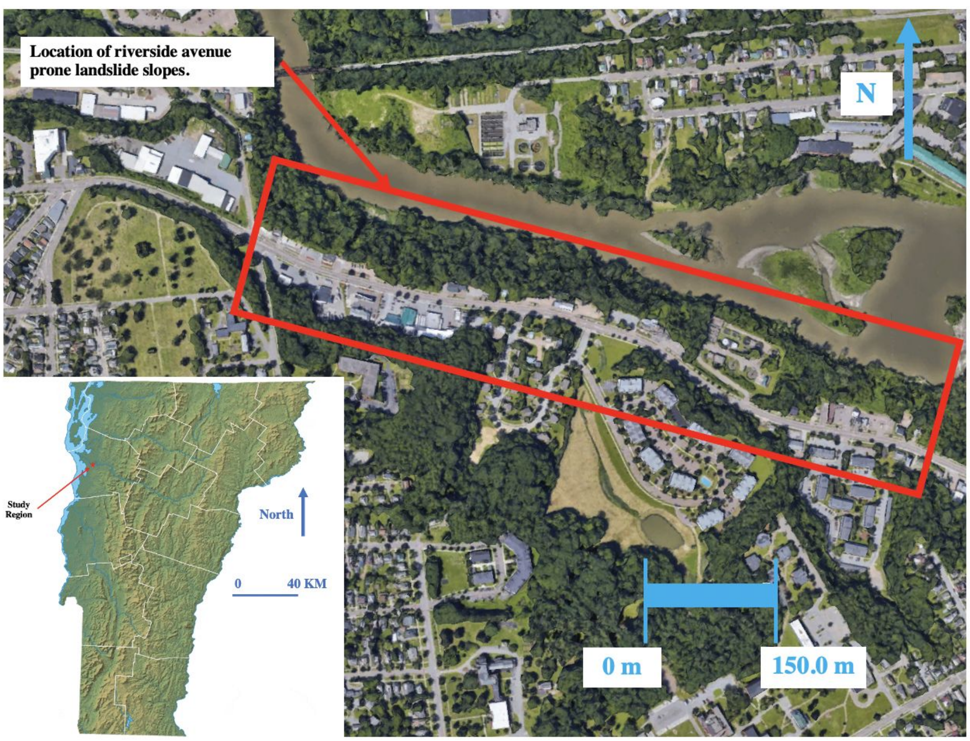

Figure 3. Figure above shows a map of Vermont, the red star indicates the study region within the state. The aerial photo above shows the cities of Burlington and Winooski VT, with the narrow slope between Riverside Avenue and the Winooski River. This is the red box that indicates the zone of past and active landslides along the busy street.

First map was taken from https://geology.com/state-map/vermont.shtml. The second aerial photograph was taken from Google Earth 2020. This figure was modified by R. Mistur.

Since the early 1930's, there has been extensive construction and road work done on Riverside Avenue, including deforestation and construction of concrete roads, curbs, sidewalks, buildings, and sewage systems, as well as efforts to improve the aesthetic quality of the area, like in 1932 when ornamental lighting was installed and the roads and sidewalks were widened (Fig. 4.). Deforestation has caused a significant decrease in slope stability, leaving the land more vulnerable in the event of excessive dumping or sudden influx of runoff. The construction of streets and buildings has caused an increase in the amount of impermeable surfaces. Increase of impermeable surfaces causes an increase in quantity and velocity of runoff, which leads to an increase of erosion along the slope.The excavation for sewer systems and implementation of culverts, has disturbed the land and increased the vulnerability to erosion. Twenty years after development of Riverside Ave began, the first three landslides occurred in 1955. (Fig. 4.) Each landslide event was followed by reconstruction attempts. We observe decades of evidence of this repeated cycle with at least five landslide events and reconstruction attempts, with the last landslide event occurring in 2019 after a large rainfall event on October 31st. At the banks of the river, there are still old appliances, large boulders, sand, silt, gravel, as well as debris, from the illegal dumping in June 1981 (Fig. 4.). The attempts to stabilize the slope have largely shown to be insufficient. The addition of sediment without compaction increases infiltration and during a rainfall event, pore pressure builds up, and sediment is likely to be transported downslope.

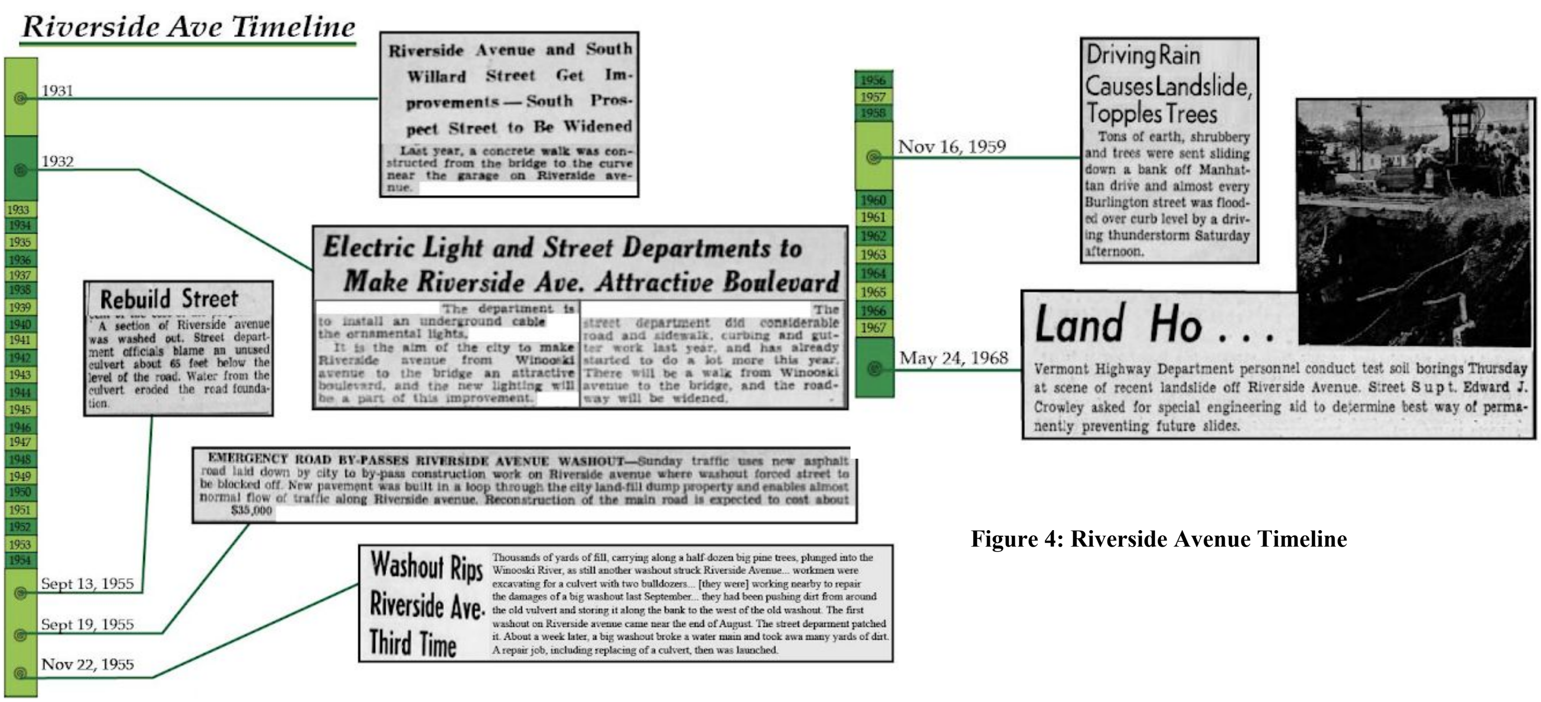

Figure 4: Riverside Avenue Timeline

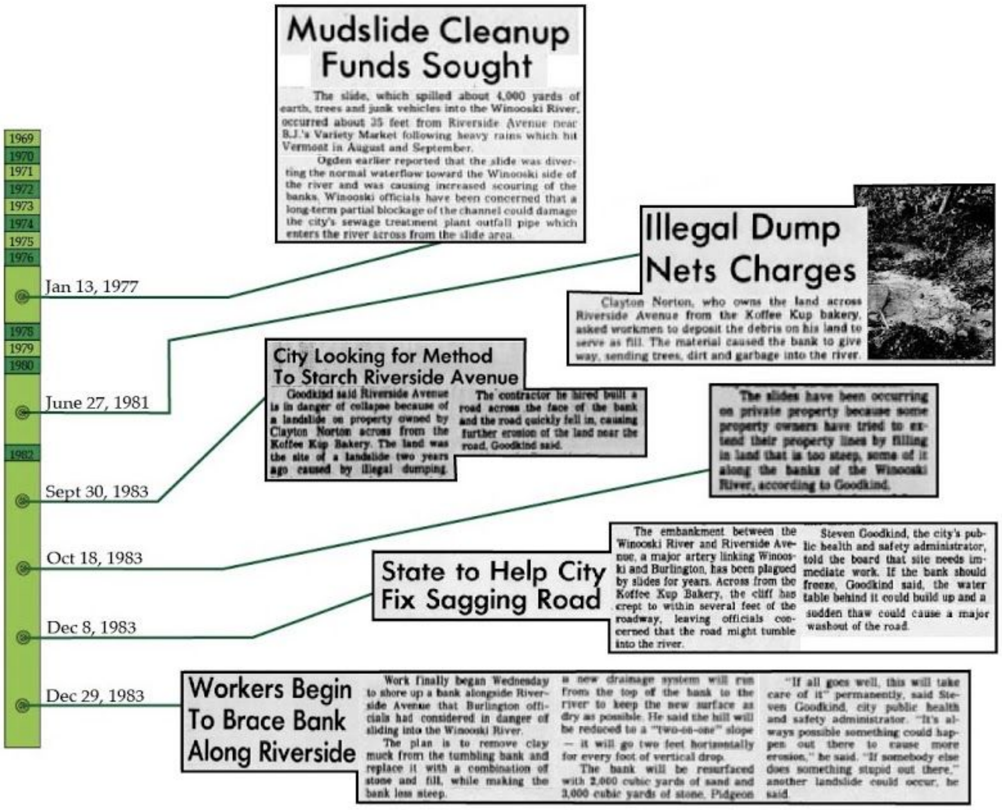

Figure 4:
Riverside Avenue Timeline (continued)
This figure illustrates the repeated trend of human activity and slope failure, and efforts of reconstruction ultimately resulting in an eventual landslide. **(**taken from UVM Geomorphology Site, modified by R. Farrell**)**

Glacial History

The recession of the Laurentide ice sheet over the last 20 kya deposited glacial till throughout Vermont and the formation of glacial lake Vermont which deposited glacial sand/clays throughout the ancient basin. (Corbett et al, 2017) The apparent cohesion of this sandy till is little to no KPa, while glacial clays have a higher cohesion value. (Fig. 5.) (Bierman & Montgomery, 2020) Landslides were most likely very active right after deposition of this material due to river incision and the absence of apparent root cohesion from vegetation along slopes. (Bierman & Montgomery, 2020) These landslides occurred as normal stress decreased due to precipitation events and pore pressures were filled, saturating the slope. Over time, the landslide activity decreased, and cohesion was added by vegetation.

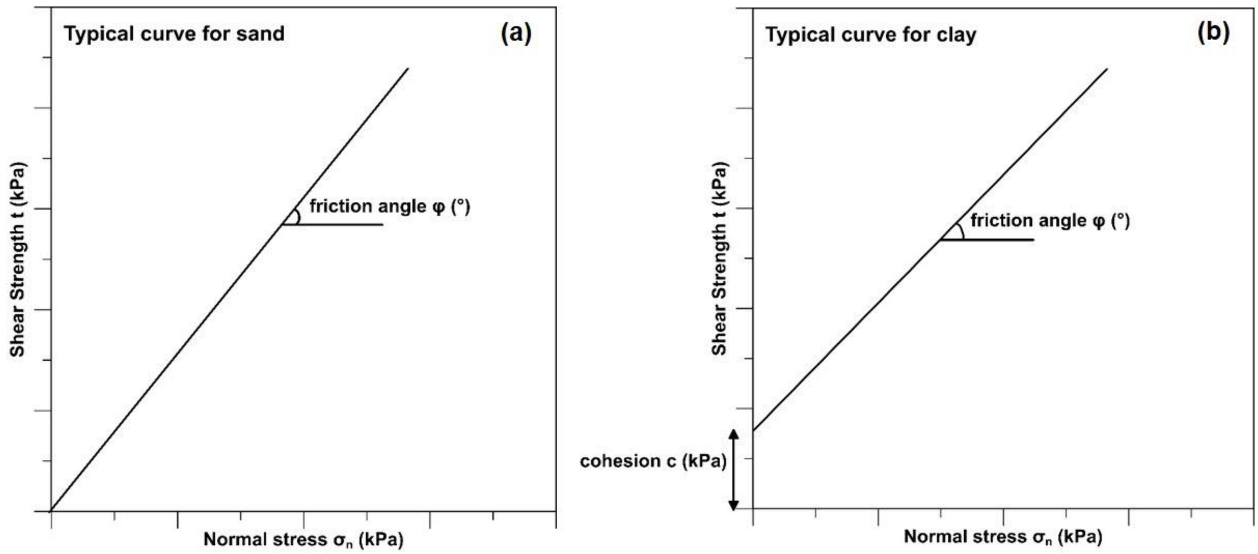

Figure 5.

Figure above shows two plots **(a)** which is the curve for sand giving a shear strength t (kPa) plotted against the normal stress (kPa) and **(b)** the curve for clay with the same variables plotted. Notice the cohesion c (kPa) value for clays, which has an internal shear strength t at 0. (Taken from https://www.geoengineer.org/education/laboratory-testing/direct-shear-test)

Hydrology

Water is the most active force of erosion. The work on Riverside Avenue has effectively disturbed the natural systems of the surface and ground water hydrology and decreased the infiltration rate of the ground. The infiltration rate is how quickly water absorbs into the soils rather than runs off. The infiltration rate is dependent on the porosity and permeability of the surface. Surfaces with low permeability will promote faster run-off, more erosion, and more transportation of sediments downslope. (Bierman & Montgomery, 2020) The addition of paved roads and buildings turned once permeable land into impermeable surfaces, causing less water to infiltrate into the ground and more water to run-off the surfaces directed down the slopes and eventually into the Winooski river. This removes the lag time since surface runoff is entering the Winooski river directly. Vegetation plays an important role in absorbing groundwater and increasing infiltration rates. The removal of vegetation reduces the infiltration rate, as well as impacts secondary porosity of the soil, leaving vacant root cavities for water to fill. There is a lag time between the peak rainfall and the peak run-off. The time it takes for an event to reach peak discharge, typically occurs quite rapidly in saturated ground, steep narrow watersheds, and areas of urbanization.

Conclusion

Due to widening the avenue with fill, removal of permeable surfaces, and loss of vegetation, these slopes will continue to fail during extreme precipitation events. Ground and surface water assessment should be done on runoff from the impermeable surfaces above and within the slope. Strategies that can help support the anthropogenic disturbed slopes of riverside avenue include planting vegetation and a runoff management system that will disperse surface water across the slope. Previous landslide scarps could use reinforcement of half meter to meter boulders, which allows for mass drainage, which reduces saturation of the slope during large precipitation events. (Ling et al, 2009) Remediation could include restoration of soil material and planting of vegetation as well as de-urbanization in the area as the slopes have proven to fail under the heightened stresses from human activity.

References:

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Corbett, L., Bierman, P., Stone, B., Caffee, M., & Larsen, P. (2017). Cosmogenic nuclide age estimate for Laurentide Ice Sheet recession from the terminal moraine, New Jersey, USA, and constraints on latest Pleistocene ice sheet history. Quaternary Research, 87(3), 482-498. doi:10.1017/qua.2017.11

Ling, H. L., Wu, M.-, Leshchinsky, D., & Leshchinsky, B. (2009). Centrifuge modeling of slope instability. Journal of Geotechnical and Geoenvironmental Engineering, 135(6). Retrieved from https://ascelibrary.org/doi/abs/10.1061/%28ASCE%29GT.1943-5606.0000024

Figure 1: Stress Diagram
Stresses Acting on a Hillslope - Created by L. Sutphen

Figure 2: Photo of Riverside Ave. Slope
Pistol Butt Trees - Photo Credit: R. Farrell
Modified and compiled by R. Farrell

Figure 3: Riverside Ave. Map
Map of Vermont - https://geology.com/state-map/vermont.shtml
Aerial Photograph - Google Earth 2020
Modified and compiled by R. Mistur

Figure 4: Riverside Ave. Timeline
Newspaper clippings - UVM Geomorphology Site, https://site.uvm.edu/geomorphology/files/2020/09/newspaper_compiled.pdf
Modified and compiled by R. Farrell

Figure 5: Typical Curves of Clay and Sand
Diagram - https://www.geoengineer.org/education/laboratory-testing/direct-shear-test