Human Activity as the Primary Indicator of Increased Frequency and Spatial Distribution of Landslides on Riverside Avenue in Burlington, Vermont, 1928 - 2019.

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Abstract (Abstract 116 words)

Recurring landslides pose a serious risk to the health, safety, and property along the northern margin of Riverside Avenue in Burlington, Vermont, USA. We investigate the recorded history of these events from 1928 through 2019 with topographic maps, city records, aerial photography, and news articles to map the temporal and spatial distribution of these slope failure events. We examine field and remote sensing data for the 2019 Halloween landslide as case study for past slope failures and incorporate an infinite-slab model. We find that slope material cohesion and saturation are the largest drivers of instability. These factors are primarily influenced by anthropogenic land use changes, thereby we suggest remediation-of-risk strategies for policy makers and land owners.

Introduction (Main Paper 1606 words)

Landslides pose a large risk to both public and private, safety and property. While most naturally covered slopes rarely fail, human land use (anthropogenic) has driven many slopes to instability. When natural landslides do occur, it is often due to an extreme weather event, earthquake, heavy rainfall, snowmelt, changes in water level, and/or erosion. Soil cohesion by plant cover plays an especially large role in maintaining slope stability throughout these events. Anthropogenic activity, deforestation, increased building of infrastructure, and the improper use of fill materials also contribute to landslide events.

We investigate one such slope between the Winooski River and Riverside Avenue in Burlington, Vermont, USA, (**Figure 1**) to provide an explanation for the recurring failures recorded from 1928 - 2019.

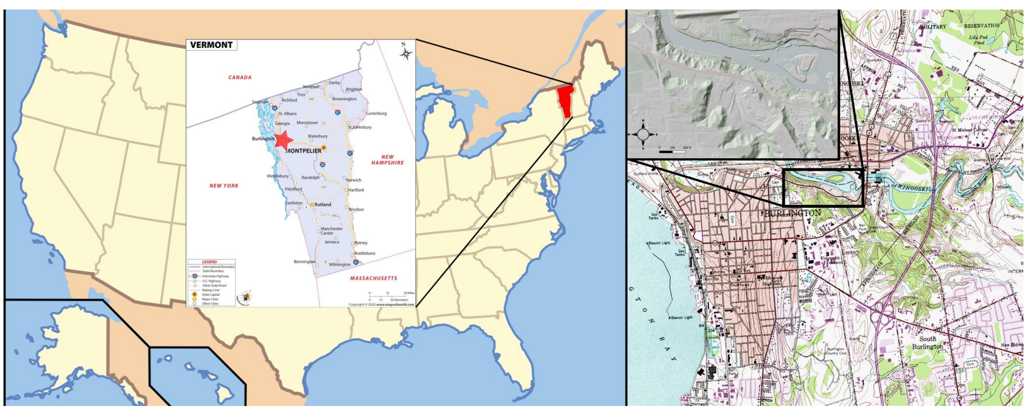

Figure 1: Map of case study location, Winooski River/Riverside Avenue, Burlington, VT, USA.

Background

To first understand the nature of landslides on the northern margin of Riverside Avenue we must look at the structure of the soils on the slope. Until ~12,000 years ago, New England was buried under the multi-kilometer thick Laurentide ice sheet. As the ice flowed over the course of millennia it eroded the underlying bedrock by glacial plucking, abrasion and freeze thaw cycles. As the ice sheet retreated clasts of rock were cemented into a platy micaceous matrix and deposited as what is known as glacial till. This glacial till is extremely pervasive across the region at depths as low as 1 meter. It forms a resistant, impermeable basement for the soils of Vermont, limiting the

Circa 1935: Efforts to stabilize and widen Riverside Avenue in Burlington included a wooden grid structure and a great deal of sand and gravel fill, as seen in this photograph by L.L. McAllister. The Fairview Garage and gas station can seen in the road's deep curve.
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Figure 2: Rebuilding a section of Riverside Ave.

saturation depth and rainwater absorption ability of the overlying temperate forested soil layers.

The first reported landslide on Riverside Avenue occurred sometime during 1928. After this event, in the 1930s, anthropogenic geomorphological impacts on the area began as Riverside Ave was expanded and paved by filling the downslope side with sand and gravel (**Figure 2**) . Circa 1937 the area was approved by the state of Vermont for development into a residential area. Following the approval, Vermonters began to build into the area, deforest the slopes, and fill ravines, decreasing soil cohesion and reducing slope stability.

Figure 3: 1955 landslides

A massive 1955 collapse of the hillside beneath Riverside Avenue in Burlington closed the road and literally undermined decades of work to stabilize the slope. This photograph was taken Dec. 8, 1955 by James Detore to document damage for the American Fidelity insurance company.

In 1948 topography changed in the area as the ravines were filled in order to make room for future housing developments and a large landfill on the south side of the avenue. In 1955 two known landslides took place at what is now the intersection of Riverside Avenue and Hillside Terrace (**Figure 3**). The first of the slides is attributed to excess soil saturation from an abandoned drainage culvert. Riverside Avenue required major repairs after a massive washout, diverting the road through the landfill. The second landslide occurred from toploading of excavation soils, overburdening the crest of the slope to the point of failure. In 1960 the landfill was dug up and cleared out, in order to make room for housing developments (see 1962 aerial photo in **Figure 4**) increasing rainfall runoff in the area.

A landslide in 1968 across from the Hillside Terrace intersection prompted an engineering evaluation of the slope but no major reinforcement was added. In 1977, 4,000 yards of earth were removed including trees and junk vehicles into the Winooski River from a landslide. In 1981 workman illegally deposited debris from an excavation site over the side of Riverside Avenue; a landslide resulted and debris flow from the landslide slid into the Winooski River. In September 1983 the city began to investigate a stone-gap procedure for landslide prevention. However, during that same year rare plants and buffer trees were removed from the slope, creating drainage problems and decreasing cohesion of the soil reducing stability of the steep slopes. By December of 1983 engineers braced the slope along Riverside Avenue by replacing glacial clay with 2,000 cubic yards of sand and 3,000 cubic yards of stone, at the same time decreasing the angle of the slope making it more gradual; reinforcement of the slope with higher-cohesion material, and reducing the slope angle proved an effective measure to prevent landslides for 36 years, until the most recent landslide in 2019.

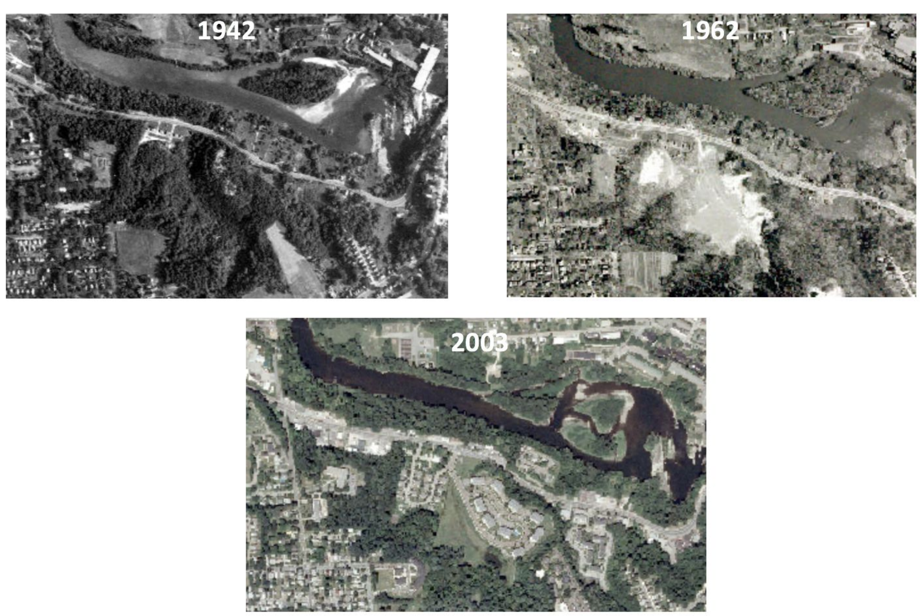

Figure 4: Three photos showing Riverside Avenue land development from 1942 - 2003. Shows well forested Riverside Ave in 1942 some development on the eastern side of the road, followed by 1962 where there is extensive deforestation making room for residential development. The 2003 photo shows development on both sides of the road with well forested hillslopes.

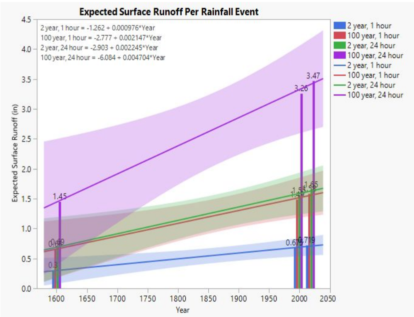

Figure 5: Expected Burlington area rainfall runoff events corrolated through time with increased population and development

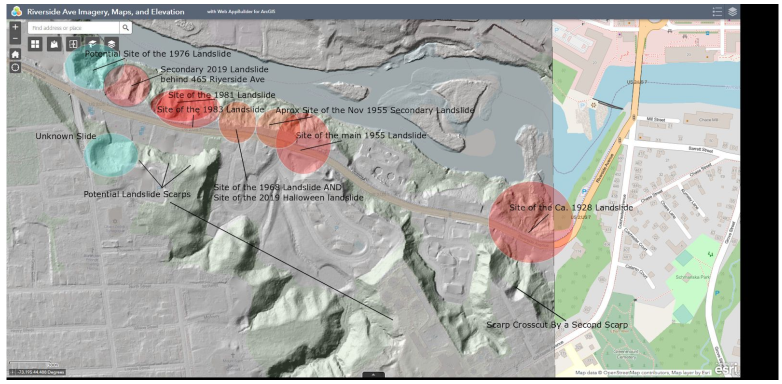

Figure 6: Distribution of recorded landslides on Riverside Avenue 1928-2019

Case Study: The 2019 Landslide

In late October of 2019, a decadal scale large storm (**Figure 5**) led to rainfall in the Burlington area of 3.3 inches over a 24 hour period. Storm runoff is exacerbated by paving, building development, and slope toploading. These factors led to slope saturation and the 'Halloween' landslide of 2019, downslope of the Hillside Terrace intersection (the same site as the 1968 landslide), and a smaller adjacent slide behind 465 Riverside Ave. A spatial and temporal distribution of a century worth of landslides on Riverside Avenue is given in **Figure 6**.

Figure 7: Drone imaging of the 2019 landslide layered on LiDAR digital elevation model of Riverside Avenue

Figure 8: Site of the "Halloween" landslide. Photo taken in Oct 2020

We Investigated the site of the 2019 Halloween landslide to gather *in situ* measurements of slope angle, debris field volume, and using orthographic LiDAR data to map the spatial extent of the scarp (Figures 7&8). Landslides occur when the driving force supersedes the resisting force. This happens to stable slopes when rainfall or runoff events increase pore pressure in soils counteracting normal forces. Using an infinite slope model these are given by:

Resisting force (s) $$s = c + (pghcos(\theta) - p'gh')tan(\phi)$$

Shear driving force (τ) $$= pghsin(\theta)$$

Where c is the material cohesion factor. p is the material density. h is failure slab thickness. g is the gravitational constant. θ is the angle of slope inclination. ϕ is the material's internal slope of friction. Primes denote water saturated variations of these parameters, which account for increases in pore pressure and an associated reduction in resisting force. Weathering processes also weaken slope materials over time, however, this model does not allow for temporal variation in our density parameters. By model sensitivity analysis, the most important factors of slope stability are the saturated depth of a slab, slope angle, and the cohesion factor.

The area of the 2019 landslide covers nearly 3500 m^2 on a 30° slope. An equal sized area of backfilled and paved property sits above and drains toward it, doubling the rainfall associated with the saturated region of the slope. By measuring the debris field volume we can estimate the slab displacement. Averaging the densities of sand, clay and gravel (fill material) we find mean dry density equal to 1600 Pa and wet density equal to 1888 Pa. This allows us to infer the cohesion factor of the slope before failure; in this instance, 1.3 kPa, well below the standard 12 kPa of soil cohesion for a forested slope.

Discussion

The history of landscape changes along Riverside Avenue include: deforestation, filling the area with sand and gravel, installing and abandoning drainage culverts, and paving the road and adjacent lots for new housing developments, reducing hillslope strength. Over the past 91 years we have seen consistent landslides along Riverside Avenue with a failure from mitigation strategies, dumping and filling practices. Repeated dumping was used over a number of years in order to provide a temporary strategy to 'stabilize' Riverside Avenue properties; as areas of the slope began to show signs of slumping (**Figure 9**), some property owners dumped fill and garbage in order to shore up the hillside, adding downforce to the top of the slopes increasing instability, illustrating a lack of knowledge of slope stability and failure.

Figure 9: Soil cracks and slumping visible on the slope at the site of the 2019 landslide months prior to failure

Burlington, Vermont is a city known for runoff issues due to the paved and sloped landscape. This is evident in the downtown area where any resident can document any rainstorm and the amount of water rushing down the streets towards the lake. The same runoff pattern occurs on Riverside Ave. The drainage on Riverside Ave proves a similar problem with the downsloping road with limited drainage leading off the road and into the sewer system or river.

Multiple residencies and commercial buildings along Riverside Ave are located in precarious areas. Examining the most recent landslide in 2019, it is clear how dangerous the slopeside is. The landslide comes within meters of a house's foundation. Looking into the future of Riverside Ave, there are essentially three main ways to address the risk of landslides. One solution is to remove any buildings in landslide prone areas eliminating a threat of loss of life. The second plan promoted by Paul Bierman, a professor of Geology at the University of Vermont is to plant trees throughout the Riverside Ave hillslope to increase the slopes cohesion reducing the chances of future

Landslides. The third remedy is an improved water drainage infrastructure plan for Riverside Avenue, sufficient to prevent large influxes of water from saturating the hillslopes during rainstorms.

Conclusion

The history of land-use change, human impacts, and slope failures helps us to understand what not to do for the future. We now have a more comprehensive understanding of why so many landslides have occurred here, from a combination of deforestation impacts, ineffective fill, dumping, and poor rainwater drainage. To help mitigate future slope failure, plans should first be made to increase slope stability. One way to do this is by an extensive, long term tree planting campaign, because plant cover has a large positive impact on soil cohesion. If a slope needs to be filled, we should use proper material with a high natural cohesion factor, like rocks, soils, and plant trees. Plans to continue development over filled areas should be avoided. Likewise, for predeveloped buildings on unstable slopes, top loading the hillside should be avoided to minimize risks to life and property. Terracing and cement supports may need to be taken into consideration. As Bierman has stated multiple times, it is highly recommended that the city buy all Riverside Avenue land on the hillslope, remove the buildings and plant trees. We've seen that even precautions and efforts to reduce landslide potential have limits. If something is not done to seriously prevent future landslides, there will be more, as the 2019 landslide is a key indication of continued instability of the area.

Citations

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