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

Hehlen, Mark. Long, Grant. Robinson, Emma. Silvia, Kate.
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Abstract (Abstract 151 words)

Recurring landslides pose a risk to 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 most recent 2019 “Halloween” landslide as a case study to help us interpret the cause of repeated slope failures and incorporate an infinite-slab model. We find that slope material cohesion and saturation are the primary drivers of slope instability. These factors are largely influenced by anthropogenic land use changes, such as deforestation, illegal dumping, urban development, and expanding lots above fill sand. Thereby, we suggest remediation-of-risk strategies including the removal of high-risk homes and buildings, re-establishing tree cover and vegetation, improving water drainage, and implementing wall terraces.

Introduction (Main Paper 1102 words)

Landslides pose a great risk to the safety and property of Riverside Avenue residents. While most unaltered slopes rarely fail, anthropogenic land use has driven many slopes to instability. When landslides naturally occur, it is often due to an extreme weather event, earthquake, heavy rainfall, snowmelt, changes in saturation, and/or erosion. Soil cohesion by vegetation plays a large role in maintaining a slope’s stability and strength. Deforestation, urban development and expansion, and other anthropogenic activity will often increase the likelihood of more frequent landslide events.

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

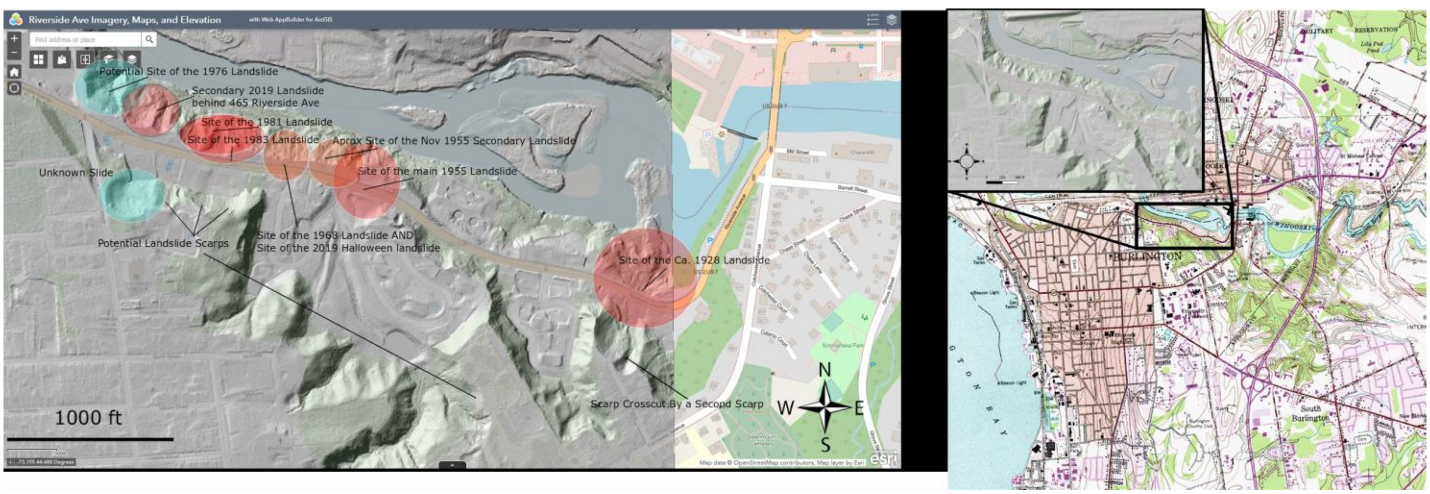

Figure 1: Location of study site in Burlington, Vermont, USA, and spatiotemporal distribution of landslides on Riverside Avenue 1928-2019. GIS Layers from https://geodata.vermont.gov/

Background

Until 14,000 years ago New England was buried under the multi-kilometer thick Laurentide ice sheet (Corbett et al, 2017). The ice sheet deposited glacial till as it retreated. This glacial till is extremely pervasive across the region at depths as low as 1 meter and forms a resistant, impermeable basement for the soils of Vermont, limiting the saturation depth. In the Champlain Valley, lake sediments were deposited while the ice sheet blocked drainage basin pathways. This defines the natural soil material on the hillslope on Riverside Avenue.

The first reported landslide on Riverside Avenue occurred circa 1928 (*History of a Slippery slope* 2019). In the 1930s, Riverside Avenue was expanded and paved by filling the downslope side with sand and gravel (*Street Department Puts 100s to Work*, 1931). Vermonters began to deforest the slopes and fill

Figure 2: Insurance photo from the historic 1955 landslide that wiped out the middle of Riverside Ave. News reports account the road detour through a landfill. From "History of a Slippery Slope" 2019.

ravines for residential development, decreasing soil cohesion and reducing slope stability.

In 1955 two landslides occurred at what is now the intersection of Riverside Avenue and Hillside Terrace. Riverside Avenue required extensive repairs after a massive washout from the first landslide (**Figure 2**). A third landslide occurred from toploading of excavation soils (*Washout Rips Riverside Ave Third Time*, 1995), overburdening the crest of the slope to the point of failure. In 1960 the landfill was cleared out, in order to make room for housing developments (see 1962 aerial photo in **Figure 3**) increasing rainfall runoff in the area.

In 1981 workers 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 (Reilly, 1981). During 1983, plants and buffer trees were removed from the slope, creating drainage problems and decreasing cohesion of the soil, thus reducing stability of the steep slopes (Donoghue, 1983). By December of 1983, engineers reduced the slope angle and reinforced it with higher cohesion materials, primarily sand and stone (Melvin, Dec. 1983).

Case Study: The 2019 Landslide

Landslides occur when the driving shear stress supersedes the resisting force (i.e. slope

Figure 3: Three photos showing Riverside Avenue land development from 1942-2003. Well-forested in 1942 with development on the eastern end of the road.1962 shows extensive deforestation for development. 2003 shows development on both sides of the road.

Figure 4: In-situ photo of the Halloween 2019 landslide and orthographic LiDAR imaging of the site. Photo by Emma Robinson. Drone imaging by UVM Remote Sensing Lab.

strength). In late October of 2019, a large storm poured 3.3 inches of rainfall in Burlington over a 24-hour period. This led to slope saturation and the 'Halloween' landslide of 2019 (**Figure 4**).

We gathered *in situ* measurements of slope angle and debris field volume, while using orthographic LiDAR data to map the spatial extent of the scarp. The area of the 2019 landslide covers nearly 3500 m^2 on a 30° slope. A ~3000 m^2 backfilled and paved property sits on the hill crest and drains upon it. Measuring the debris field volume, we estimate a slab displacement of 3595-5000 cubic meters. Observed debris consists of sandy soils, shrubbery, tires, cement blocks, and trash.

To model the 2019 landslide, we invoke the infinite slope model (**Figure 5**), which accounts for slope plane angle, gravity, slab height, dry and water saturated density of material, material internal angle of friction, pore pressure, and cohesion. Model sensitivity analysis shows that slope angle, cohesion, and saturated slab thickness are the primary drivers of failure. With this model and available data, we can infer the material cohesion before failure (See Supplementary Material I); in this instance, 1.2 kPa, well below the standard 12 kPa of soil cohesion for a forested slope. Low soil cohesion from deforestation coupled with the increased drainage area from the paved toploading property placed this slope at high risk of failure.

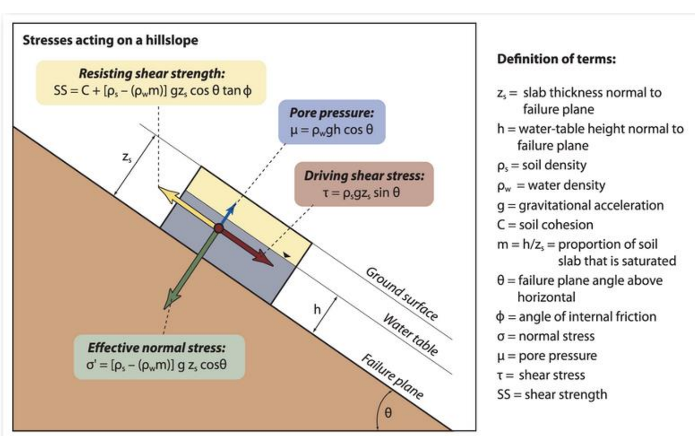

Figure 5: Infinite-Slope landside model, adapted from Bierman and Montgomery (2020)

Discussion

Anthropogenic landscape changes along Riverside Avenue include deforestation, filling the area with sand and gravel, installing and abandoning drainage culverts, and paving for new developments (Melvin, Dec. 1983; Donoghue, 1983); all reduce hillslope strength. Over 91 years we have seen consistent landslides along Riverside Avenue and a failure of mitigation strategies. Repeated dumping over a number of years attempted to provide 'stability' to Riverside Avenue properties; some property owners dumped fill and garbage in order to shore up the hillside and expand usable property area (Melvin, Sept. 1983), adding pressure to the slope, increasing instability.

Urban areas incur excess runoff due to impermeable pavement and developments. Runoff on Riverside Avenue is no exception. The down sloping road with limited drainage leading off the road and into the sewer system or river. By analyzing land-use change in Burlington, runoff percentage, and storm recurrence rates, we can see a clear trend in increased runoff (**Figure 6**) that will threaten unstable slopes - and the buildings on them - more often in the future.

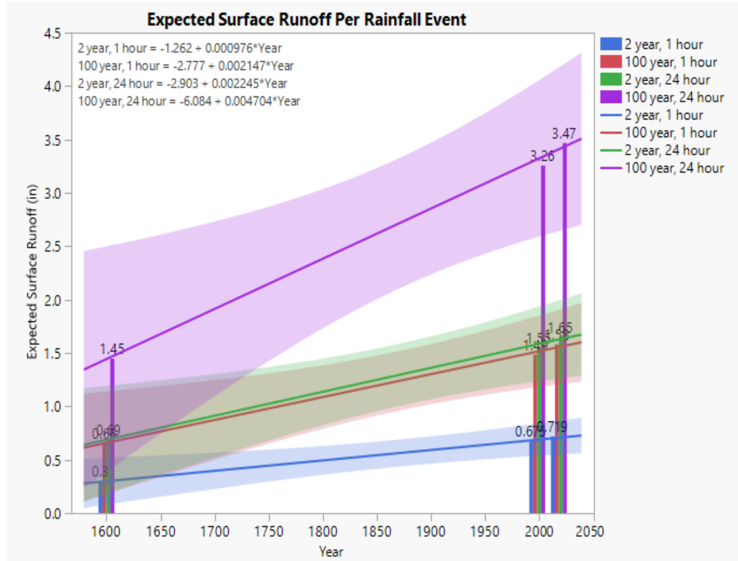

Figure 6: Expected Surface Runoff in Burlington, Vt. Runoff increases with land use change and urban development. Made with calculated data from Burlington Orthophotography and Rainfall recurrence events from US Department of Commerce and Weather Bureau (1959)

Looking to the future of Riverside Avenue we pose four strategies to address landslide risk. One is removal of buildings in landslide prone areas eliminating the threat of loss of life. The second plan developed by Paul Bierman is to plant trees throughout the Riverside Avenue hillslope to increase soil cohesion. 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. The final plan is to implement retaining wall terraces to reduce slope angle and mitigate the damage of any mass-movements.

Conclusion

Learning from land-use change, human impacts, and slope failure helps us understand what to do for the future of Riverside Avenue. We now have a comprehensive understanding of why landslides occurred here, from a combination of deforestation impacts, ineffective fill, dumping, urban development, and poor rainwater drainage. To help mitigate future slope failure, plans should first be made to increase slope stability. The simplest of which is an extensive, long term tree planting campaign, as plant cover and root systems have a large positive impact on soil cohesion. Plans to continue development over filled areas should be avoided. Terracing and cement supports should be taken into consideration. We've seen that even precautions and efforts to reduce landslide potential have limits. If no solution is addressed to prevent future landslides, there will certainly be more, as the 2019 landslide is a key indication of continued instability of the area.

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Supplementary Information (1)

The infinite slope model is given by

Resisting force (s) $$s = c + (pghcos(\theta) - p'gh')tan(\phi)$$ [1]

Shear driving force (τ) $$\tau = pghsin(\theta)$$ [2]

Where c is the material cohesion factor. $p$is the material density. $h$is failure slab thickness. $g$is the gravitational constant.$\theta$is the angle of slope inclination.$\phi$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. Given sandy-fill material's internal angle of friction is ~30° our case study simplifies with θ= ϕ= 30°. When forcing the condition s=τ (slope failure), the equations collapse to:

$$c = \frac{\sqrt{3}}{3}p'gh'$$ [3]

Averaging the densities of sand, clay and gravel (fill material) we find mean dry density of p =1600 Pa and wet density of $p' =$ 1888 Pa. Given the gravitational constant and our , we find:

$$c = 10682.4h'$$ [4]

Given the increased runoff from Riverside Avenue and the toploading development, we can vary $h'$to find potential values for c.

TABLE 1:

h'(m)	c(Pa)
0.0587	627.055
0.0881	940.582
0.1174	1254.11

TABLE 2: 2019 Landslide Data

Slope Angle	30°	Debris Field Height (min) (m)	2.1845
Width (m)	52.4256	Debris Field Height (max) (m)	3.0480
Length (m)	31.3944	Surface Area of Slope (min) (m^2)	3251.6930
Vertical Relief (m)	34.9999	Surface Area of Slope (max) (m^2)	3524.6200
Rainfall Event (m)	0.0838	Slab Vol (min) (m^3)	3595.4060
Absorbed Rainfall increment (m)	0.0587	Slab Vol (max) (m^3)	5016.6130
Height of Slab (min) (m)	1.0201	Height of Slab (max) (m)	1.5428