Geomorphology and Landslides Along Riverside Avenue

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Abstract (209 words)

Riverside Avenue, along the south side of the Winooski River as it flows through Burlington, VT, has a long and problematic history of landslides linked both to the natural landscape and to human development. As the last ice sheet retreated from New England, a thick layer of loosely cohesive sediment was left behind. This sediment forms the banks of the Winooski River and as the river incised, the slopes formed were prone to slide. Though road development started before 1872, the forests and slopes were left intact enough for the slope to remain stable. However, later development near the slope's edge brought marked changes in vegetation type and density, and water flow. These changes resulted in 9 reported landslides along Riverside Avenue between 1955 and 2019. In order to stabilize the bank, fill was repeatedly dumped on the shore. Landslides are still common and they continue to pose a danger. There are several geoengineering solutions available, though all are resource intensive. The crib wall check dam may be the most applicable approach for the Riverside Avenue slope. However, a public education campaign could be more effective in its ability to re-alert citizens of the danger and lobby for a city initiative to help businesses along that corridor to relocate.

Glacial History (total 1183 words)

After the retreat of the Laurentide ice sheet, a thick layer of glacial lake sediment and till occupied much of the Champlain Valley. When river systems reestablished, they incised into sediment of the lower valley (Roussel, 2018). Along the Winooski River, steep slopes and degradational terraces were formed in the sediment banks along what is now Riverside Ave. Figure 1 shows how river incision through glacial sediments creates steep and unstable slopes of glacial sediment and till (Phillips, 2005). These slopes eventually stabilized through forestation, soil creep and other processes over thousands of years.

Figure 1: A degradational terrace with a steep, unstable slope on the far side of the river
Photo sourced from Bethan Davies, 2004

Anthropogenic and Natural Influences on Riverside Ave Landslides

Landslides along Riverside Avenue may have occurred before development, but human intervention has likely made them larger and more frequent. Slopes initially formed by glacial retreat or fluvial incision, while initially unstable, usually settle and stabilize as the slope angle is lowered due to mass movement and as forest root systems mature and increase cohesion. Deforestation along this slope destabilized it by removing and disrupting the deep root systems that held the slope in place. Additionally, the dumping of low cohesion fill material created steep and unconsolidated slopes. Development has also increased the runoff onto the bank by creating impervious surfaces surrounding Riverside Avenue. Figures 2.1 and 2.2 provide a brief history of human changes and landslides over the last century. However, some factors on Riverside Avenue are natural and unavoidable, such as the steep slope, and erosion at the bottom due to the Winooski River. While the slope is naturally steep, human-induced changes have had a large impact on landslides in the last century (Highland and Bobrowsky, 2008).

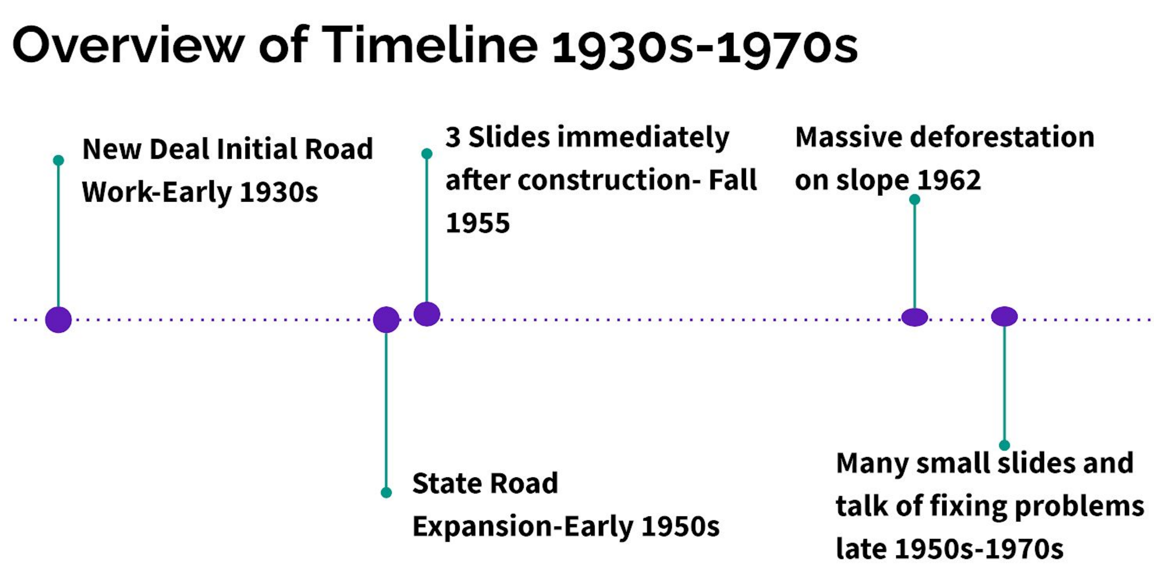

Figure 2.1 highlights key events relating to landslides along Riverside Ave between the 1930s and 1970s

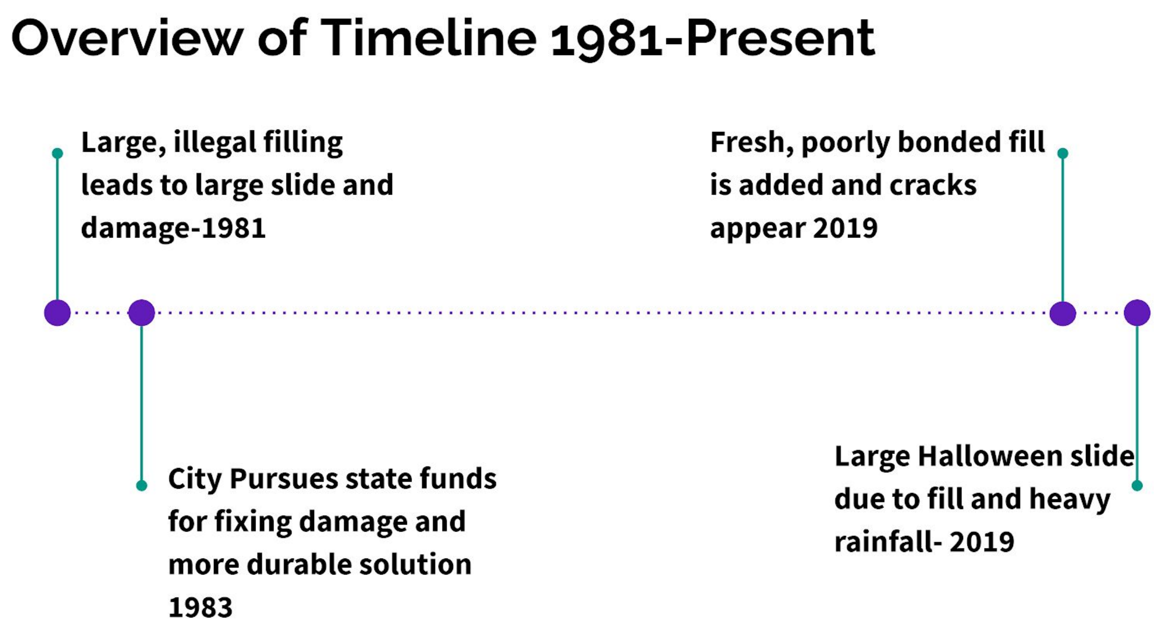

Figure 2.2 highlights key events relating to landslides along Riverside Ave between the 1930s and 1970s

Landslide Triggers and Hydrology

Landslides are triggered when shear stress becomes higher than the shear strength of a slope. Heavy rainfall may saturate the slab, increasing pore pressure and slab density. Deforestation also contributes to reduced shear strength since root networks are critical in holding material in place. The material comprising the slab influences stability. In slopes with clay-rich material, the hydrogen bonding between adsorbed water molecules and the clay mineral surfaces increases cohesion strength. Figure 4 demonstrates the large range of cohesiveness of different materials.

	Effective Friction Angle, ϕ' (°)		Effective Cohesion, c' (kPa)
	Peak	Residual	
Gravel	34	32	-
Gravel, sandy with few fines	35	32	-
Gravel, sandy with silty or clayey fines	35	32	1.0
Gravel and Sand mixture, with fines	28	22	3.0
Sand, uniform, fine grained	32	30	-
Sand, uniform, coarse grained	34	30	-
Sand, well graded	33	32	-
Silt, low plasticity	28	25	2.0
Silt, medium to high plasticity	25	22	3.0
Clay, low plasticity	24	20	6.0
Clay, medium plasticity	20	10	8.0
Clay, high plasticity	17	6	10.0
Organic Silt or Clay	20	15	7.0

Figure 3: A table of cohesiveness for different materials. *Sourced from ABG Creative Geosynthetic Engineering -- Soil Properties: Shear Strength, 2020.*

Fill may initially stabilize a slope, but it is generally less cohesive than undisturbed material that is reinforced by root systems and years of settling. When fill was dumped prior to the 1981 and 2019 slides, it was placed at the top of the slope in an attempt to replace lost material. However, this added mass to the head of the slope and increased the driving force, priming the site for a slide.

In undisturbed slopes, infiltration and run-off patterns are established and stable. When paving was increased along Riverside Avenue, more surface water flowed onto the top of the slope and infiltrated into the soil. The greater water infiltration increased the pore pressure and may have raised the water table. Elevated water table levels also contribute to slope destabilization. Below the water table, pores and fractures in the soil fill up with water and increase pore pressure of the slope material (Brönnimann, 2011). This increased pore pressure reduces the frictional forces within the slab and thus dramatically reduces shear strength (Soil Properties: Shear Strength, 2020).

Rising water tables (and therefore pore pressure) are often caused by heavy amounts of precipitation. In the case of Riverside Avenue, a flash flood on the night of Halloween in 2019 deposited 3.3 inches in Burlington. The heavy rainfall was quickly followed by a devastating landslide, following a similar pattern as many other slides in the area. The average time between a flood of a certain magnitude, or the recurrence interval, is also a key factor to slide probability. This interval is based on a frequency curve developed using records from the USGS gauge located on the Winooski River. At the Essex Junction Stream Gauge, the recurrence interval is calculated to be 3.44 years for a flood the size of the 2019 event. Given this relatively short interval and the destruction that the storm on Riverside Avenue caused, one may expect more slides in the future (Federal Emergency Management Agency, 2013).

Spatial Distribution and Causes of Landslides along Riverside Avenue

To the first engineers constructing Riverside Avenue, the steep slope north of the road was not a concern as the mature forest was a clear sign of slope stability. However, with development, the river bank now comes as close as 76 meters from the edge of the pavement in some areas. With an estimated relief from river to road of 37.5 meters, slope in some areas may be as steep as 26 degrees. Near the intersection of Riverside and Intervale Avenues the river bends to the north and tends to emplace a cutbank. All these conditions conspire to make the north side of Riverside Avenue a perfect setting for landslides. Prior to human intervention, landslides were likely rare and small, but with deforestation, paving and dumping of fill, landslides became larger and more frequent. Now, they pose imminent danger to properties in this area. Most of the landslides have occured along the western half of the Avenue where the slopes are steeper. Moreover, applications of fill occurred primarily in this region, which significantly decreased resisting shear strength of the slope's material, thereby reducing the resisting forces and increasing the chance of slope failure.

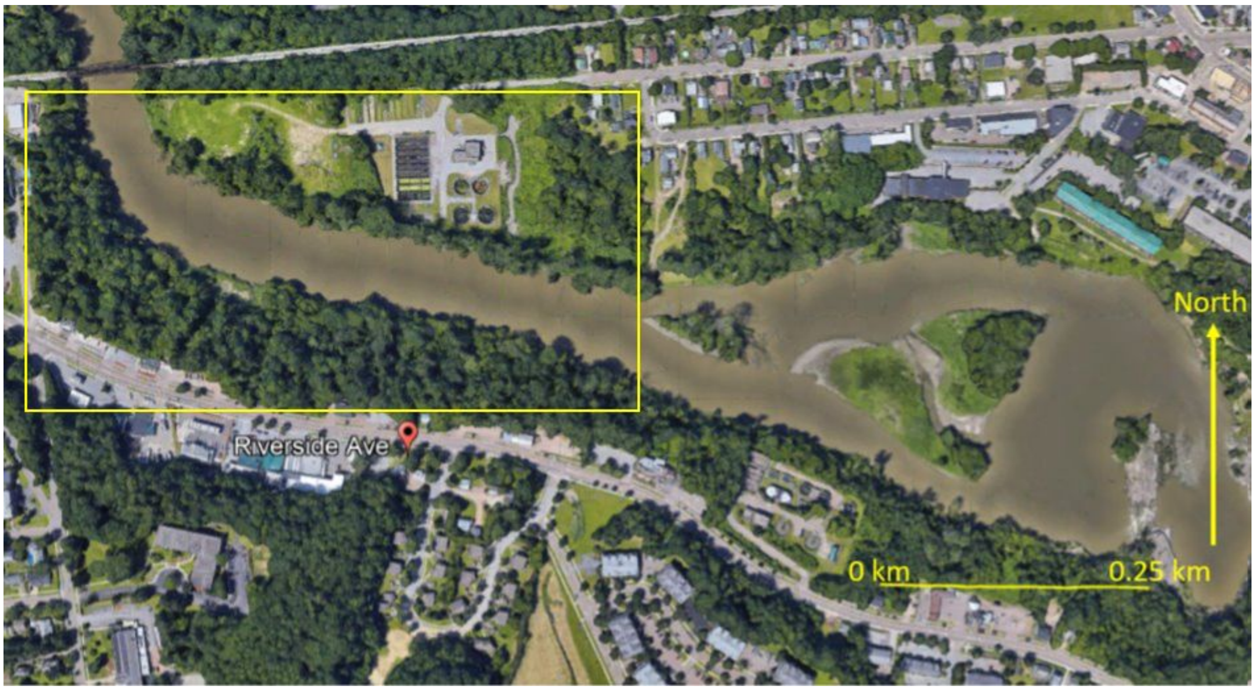

Figure 4: This image of Riverside Ave shows the extensive development and impervious surfaces built on the edge of a 76m high slope leading to the river. The yellow rectangle represents our study area. *Photo sourced from Google Maps, 2020.*

Risk Mitigation and Public Education

Any viable proposal to stabilize the slope along Riverside Avenue must have the goal of either reducing the driving force of slides and/or increasing the shear strength of the soil mass. Rock fill buttressing has already been used effectively along this area. This strategy increases stability by adding heavy and very coarse blocks along the base of the slope. This material has a high internal friction angle and drains quickly, thereby reducing slope saturation. Another option is the use of horizontal pipes to help soil drainage and reduce pore pressure as shown in Figure 5. These pipes are built into the slope with the buried end of the pipe below the water table and the exposed end of the pipe draining to the surface at the bottom of the slope of concern. When done correctly, accounting for hydraulic and geologic aspects of the slope, this method prevents slab saturation and assists in slope stability (Highland and Bobrowsky, 2008). However, they will be difficult to place in the confined area of Riverside Avenue where landslides encroach upon the river and there is no access to the shore for heavy machinery.

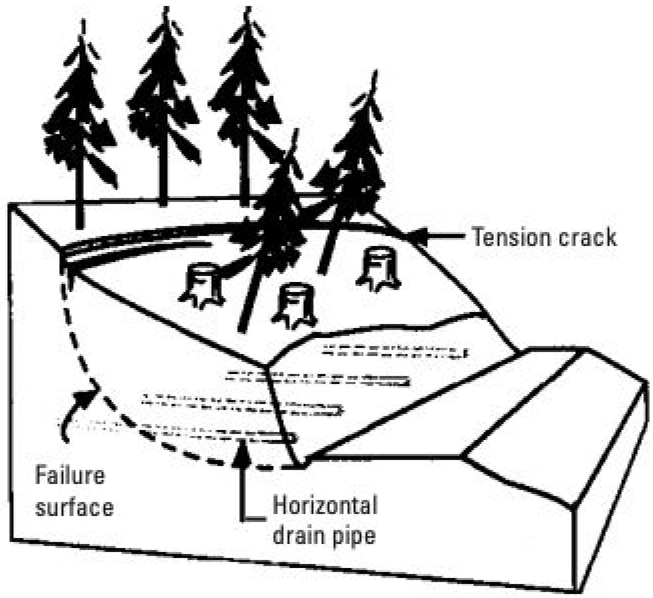

Figure 5: Schematic of drain pipes. Note that the pipes are placed below the failure surface. (Highland and Bobrowsky, 2008).

Equally important will be education of city officials and the general public regarding the landslide danger in this area. During heavy precipitation events residents living near a high landslide risk area should remain alert to sounds that could indicate moving debris, such as trees cracking or boulders knocking together. Any sudden increase or decrease in water flow or a change from clear to muddy water can indicate a debris-flow upstream. Residents should be prepared to move quickly. Eventually one or more of these businesses on Riverside Avenue will need to be relocated. The city could facilitate the move by starting an escrow account to help the businesses make the move. The city could also implement monetary incentives in order to make these moves feasible.

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