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Review on Hydraulic and Geotechnical Mechanisms of Riverbank Roadway Erosion and Collapse

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ABSTRACT

Riverbank erosion is a critical geomorphological process with significant impacts on river systems and adjacent infrastructure. In many regions, transportation networks are constructed near riverbeds, making them susceptible to bank instability and erosion. Hydraulic forces including flow velocity, turbulence, and shear stress play a major role in determining the rate of riverbank erosion. Concurrently, the geotechnical properties of bank materials, such as cohesion, permeability, and soil structure, influence the riverbank's resistance to erosion and slope failure. The interplay between hydraulic dynamics and soil mechanical properties results in various bank failure mechanisms, including rotational slip, cantilever failure, and block failure. Additionally, traffic loads and human activities can exacerbate the instability of riverbanks adjacent to transportation infrastructure. This paper reviews previous researches on riverbank erosion, soil characteristics, hydraulic flow conditions, and the instability of roads near rivers. The review aims to identify the key factors controlling riverbank erosion and to highlight existing research gaps, particularly regarding the combined effects of hydraulic loading and traffic-induced stresses. A comprehensive understanding of these mechanisms is essential for developing effective strategies to stabilize riverbanks and safeguard transportation infrastructure.

1. Introduction

Riverbank erosion is a natural process that plays a fundamental role in shaping river channels and floodplains. However, excessive erosion may result in severe environmental and engineering problems, particularly when infrastructure such as roads, bridges, and pipelines are located near riverbanks. Many transportation corridors are constructed along rivers due to topographic and economic considerations, making them highly susceptible to erosion-induced failures. Riverbanks hold great significance. Historically, human populations have gathered around rivers and beaches to utilize natural resources such as transportation, agriculture, and fishing. In recent decades, several researchers have sought to understand and quantify the mechanism of bank erosion through field and laboratory studies [1]. Erosion of riverbanks refers to the erosion of bank material by transported sediment or flowing water [2]. The flow of water overcomes the strength or shearing resistance of the materials or sediments at the base of a riverbank. The sediments at the base

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of the bank are eroded by flowing water (during elevated discharge or groundwater outflow into the river), creating a vacuum at the base and resulting in a steep wall or edge that ultimately collapses due to hydraulic pressure, geotechnical factors, or combination of both. The loss of materials from a river's banks is a dynamic natural process known as river bank erosion, an inescapable and natural phenomenon[3]. There are two types of factors that contribute to this phenomenon [4] : natural (such as climate parameters like rainfall type, intensity, and variability, or soil properties like water content, shear strength, and vegetation type) and human (such as dam construction, logging, and intensive grazing) [5]. The phenomenon of riverbank collapse in the affected regions encompasses various bank and riverbed deformations, including longitudinal erosion and sediment deposition on the riverbed, as well as transverse alterations of riverbed channels. Recent studies have also emphasized the role of anthropogenic factors in riverbank instability. Infrastructure loading, traffic vibration, land-use changes, and river engineering interventions may alter natural bank stability. These factors often interact with hydraulic forces and soil mechanical behavior, resulting in complex failure mechanisms. Therefore, understanding the combined influence of hydraulic conditions, geotechnical properties, and external loading is essential for developing effective riverbank stabilization strategies [6]. Riverbank failure is influenced by various elements, particularly during the wet season, including fluctuations in river water level (RWL), groundwater, pore water pressure, soil strength (soil suction and shear strength), and soil erosion. The primary mechanisms of riverbank collapse identified in prior research include planar failure and cantilever failure, which indicate that the correlation between soil hydraulic properties and the rate of RWL change is the principal factor influencing these mechanisms and riverbank stability [12].

This study encompasses the following sections**:** Section 2 provides an overview of riverbank erosion mechanisms, highlighting the main types and influencing factors. Section 3 discusses the geotechnical properties of riverbank soils, including the key soil characteristics that affect their stability. Section 4 focuses on the hydraulic factors that control riverbank erosion and their role in initiating erosion. Section 5 addresses the instability of roads near riverbanks, with particular emphasis on the impact of traffic loads on bank stability. Based on a literature review, a research gap was identified regarding the limited number of studies addressing the combined effects of hydraulic flow and traffic loads. Therefore, this study proposes a modeling methodology to investigate this interaction and its impact on riverbank stability.

2. River-bank Failure mechanisms

Bank failure occurs when the (moment of) driving forces (weight of the slipping block and positive pore water pressure) acting on the most critical slip surface exceeds the (moment of) resisting forces (Coulomb friction, apparent cohesion forces and hydrostatic confining pressure in the river) following an increase in bank height and slope due to bank-toe erosion [7] [8]. Stability of the riverbank is commonly expressed in terms of a safety factor, which is defined as the ratio of resisting forces to the driving forces. Riverbank fails when the safety factor is less than 1, and is conditionally stable when it is between 1 and 1.3 [8] [9] [10].In non-cohesive soils, the driving force in the shear failure of the riverbanks is the shear stress on the failure plane due to the component of the weight in down slope direction. The resisting forces include the shear strength of the potential failure plane due to the internal friction as shown in figure1 [11].

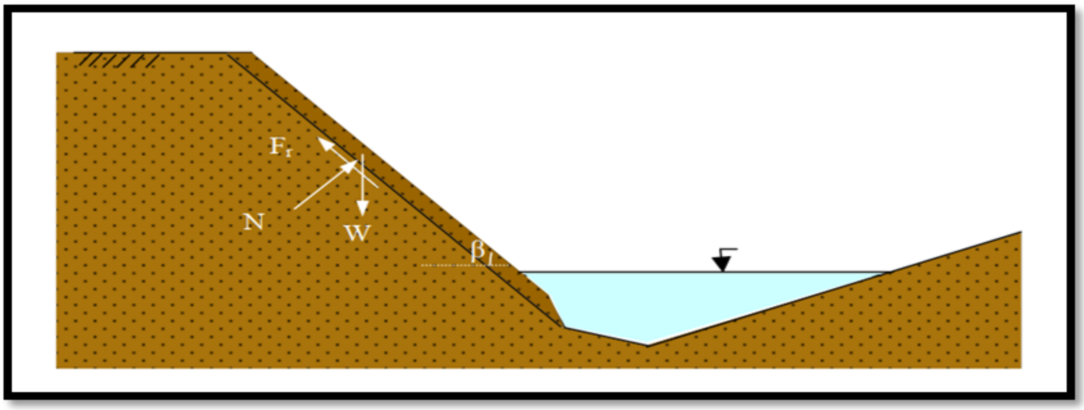

Figure 1. Shear failure of non-cohesive banks [11].

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Riverbank collapse occurs through several geomorphological and geotechnical mechanisms that are strongly influenced by hydraulic conditions and soil properties. According to [13], seven main mechanisms of riverbank failure have been identified: rotational slip, cantilever failure, soil fall, dry granular flow, and wet earth flow as shown in figure 1.These shallow slide, slab failure,

mechanisms range from shallow surface sliding in weakly cohesive soils to deep-seated rotational failures involving large soil masses, as well as cantilever collapse caused by toe erosion and undercutting. Other processes such as soil fall, granular avalanching, and wet earth flow are commonly associated with bank steepening, soil saturation, and high pore water pressure. The occurrence of these mechanisms reflects the complex interaction between hydraulic forces, soil strength, and bank morphology. Such processes can significantly reduce the stability of riverbanks and may threaten nearby infrastructures, including roadways constructed along river margins [13].

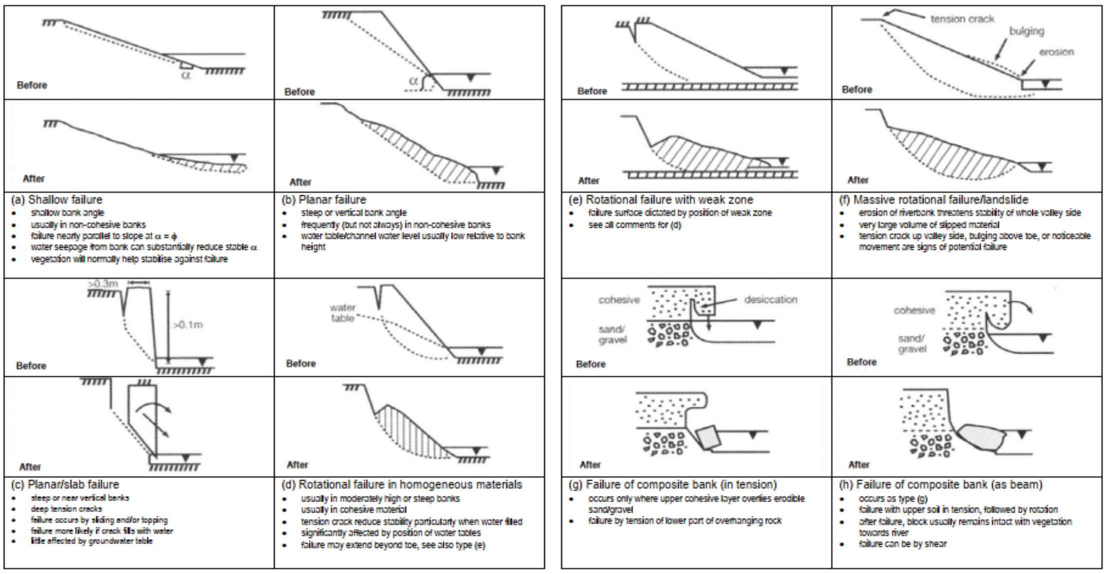

Figure 2. Bank failure mode [14]

3. Geotechnical Characteristic of Riverbank Soils

These mechanisms range from shallow surface sliding in weakly cohesive soils to deep-seated rotational failures involving large soil masses, as well as cantilever collapse caused by toe erosion and undercutting. Other processes Regarding the factors influencing riverbank collapse, soil physical properties, particularly grain size and density, are key factors affecting both river erosion rate and bank stability [15] [16] [17]. Samade et al. [15] conducted the first experiment involving the creation of an embankment on a riverbank to understand the mechanism of embankment collapse. The experimental results were compared with those obtained from a numerical simulation model. By analyzing riverbank soils of varying densities, Samade and colleagues obtained similar results. Studies (2011, 2013) concluded that as soil density increases, so does the depth of erosion at which collapse occurs, as well as the ratio of the upper to lower embankment width under collapse conditions.

The response of soil to hydraulic forces depends largely on its classification and physical properties. Coarse soils (sand and gravel) are typically characterized by high permeability and low cohesion, making them prone to particle separation under moderate flow. Fine soils, especially clay, resist erosion due to their cohesion, but may become loose and crack over time [18].

4. Hydraulic Factors Controlling Riverbank Erosion

Bank erosion is of fundamental importance to the morphodynamics of fluvial, estuarine and coastal environments, affecting a wide range of physical, ecological, and socioeconomic processes. Bank erosion is commonly categorized in to flow-induced bank erosion and bank collapse[19] [20]. Bank collapse occurs when the driving forces that tend to move soil downslope (e.g., the weight of soil and plants, positive pore water pressure, and seepage forces) exceed the resisting forces of the bank (e.g., soil cohesion, matric suction, hydrostatic pressure, and vegetation roots) [21] [22]. Erosion studies have shown that fine-grained soils like silts and clays may resist erosion initially due to cohesive bonds, but once these are overcome, they degrade rapidly. Conversely, sandy soils, though less cohesive, erode more consistently at lower velocities due to weak interparticle forces. Critical velocity values vary, but typically range from 0.2–0.6 m/s for fine sediments and 0.6–1.5 m/s for coarse sands [23] .

River flow plays a fundamental role in controlling riverbank instability through its direct influence on both hydraulic conditions and bank morphology. Changes in flow characteristics can modify the bank slope gradient and alter the flow structure following riverbed deformation, which in turn accelerates the initiation of bank failure and facilitates the breakdown and transport of collapsed materials. In particular, the concentration of flow velocity near the riverbank increases the transverse velocity gradient toward the bank, resulting in steeper near-bank slopes and a greater likelihood of instability and collapse [24]. Furthermore, the erosive capacity of a river is closely related to the tractive force exerted by flowing water, which increases with channel slope, flow velocity, and water depth. As flow velocity increases, the river gains greater capacity to erode bank materials, leading to progressive bank retreat and channel adjustment. In many natural rivers, erosion along one bank is often balanced by sediment deposition on the opposite bank, which allows the channel to migrate laterally or develop meanders while maintaining an approximately constant width [25]. These processes highlight the strong interaction between hydraulic forces and bank materials, emphasizing the critical role of flow dynamics in governing riverbank erosion and collapse.

5. Roadway Instability Near Riverbanks

Highways constructed near riverbanks are often partially filled or excavated, making them vulnerable to long-term river erosion, flooding, and landslides. These processes can result in degradation of the roadbed, displacement or cracking of pavement, and pose significant risks to transportation safety and the surrounding communities [26]. Traffic loading may further increase the risk of slope failure by introducing additional stresses into the soil mass. Repeated loading from heavy vehicles may accelerate crack formation and reduce soil strength, particularly in saturated conditions.

Several case studies have documented roadway failures caused by riverbank erosion. These failures often occur when hydraulic erosion undermines road foundations while traffic loading simultaneously weakens the soil structure[27].

6.Conclusions

Previous studies have shown that riverbank erosion and collapse are complex phenomena resulting from the interaction between hydraulic factors and the geotechnical properties of the soil. Hydraulic variables, such as flow velocity, shear stress, and water level fluctuations, play a major role in initiating and developing the erosion process, while soil properties, including grain size distribution, density, cohesion, and shear strength, directly influence the bank resistance to erosion and collapse.

The literature also indicates that riverbanks can be subject to various types of failure, such as rotational failure, cantilever failure, surface slippage, and grain collapse, depending on the soil type and prevailing hydraulic conditions. Studies have further confirmed that roads and structures located near riverbanks are among the most vulnerable infrastructure to damage resulting from bank erosion and instability.

Despite numerous studies addressing riverbank erosion and stability, most have focused on hydraulic or geotechnical aspects in isolation. Research investigating the combined impact of water runoff and recurring traffic loads on the stability of roads adjacent to rivers remains relatively limited. The findings of this review indicate a significant knowledge gap regarding the interaction between these two factors and their simultaneous influence on the stability of riverbanks and the roads constructed near them. Therefore, this study aims to address this research gap by developing a laboratory-based physical model to investigate the combined impact of water runoff and recurring traffic loads on the behavior of riverbanks and the roads built upon them. The goal is to evaluate potential failure mechanisms, identify the most influential factors in the stability of these systems, and ultimately provide engineering recommendations to mitigate collapse risks and protect infrastructure adjacent to rivers.

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