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A comprehensive fluvial geomorphology study of riverbank erosion on the Red River in Winnipeg, Manitoba, Canada

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SUMMARY

Riverbank erosion on the Red River in Winnipeg, Manitoba has raised concerns over the last 20 years and more. Although several recent studies have shown that fluvial erosion can reduce riverbank stability and promote geotechnical slope failure, there are too few that have focused on this phenomenon. The present study includes field measurements, experimental testing, and numerical modelling to quantify fluvial erosion through a 10 km reach of the Red River. Results have shown that seasonal freeze–thaw processes can dramatically reduce the critical shear stress and increase erodibility of the riverbanks. Moreover, a simple method has been employed using hydrodynamic numerical models to define the applied shear stresses on the river banks based on the river water level, which will be useful for further research and design purposes. The TEMP/W numerical model was used to define seasonal frost depth to estimate freeze–thaw effects. Finally all field measurements, experimental and numerical models results were used to predict annual fluvial erosion through this reach of the river.

1. Introduction

Riverbank erosion has physical, ecological and socio-economic effects on fluvial environments (Rinaldi and Darby, 2007). Riverbank erosion has two important consequences: (1) land loss during fluvial or slope failures that can cause economic losses or safety issues; and (2) impact on downstream water quality, such as increased turbidity and sediment concentration which may be harmful for aquatic environments. One of the main differences between riverbanks and riverbeds is the direct contact of riverbanks with the surrounding environment; therefore changes in weather and climate have a more direct influence on riverbank behavior. Riverbank erosion is a function of its soil properties, and any change in the soil structure may change the soil behavior. These effects are significant in cohesive soils since clay particle behavior is highly impacted by any natural or engineering process that changes the physical relationship between these particles (Torrance, 1975). In Canada, subaerial processes like seasonal freeze–thaw are the most common physical processes that can affect riverbank soil properties (Graham and Au, 1985). In particular, Manitoba in Western Canada is famous for its severe cold weather during the winters. Thus, it is essential to understand the effects of freeze–thaw processes on riverbank erodibility, in addition to the effect of various hydraulic factors.

The main riverbank failure mechanisms are: (1) fluvial or hydraulic erosion due to the applied shear stress induced by flow or waves; (2) geotechnical slope failure due to the variation of effective stress and pore water pressure through the soil structure; (3) a combination of fluvial and geotechnical failures, which is especially common in composite banks. Quantifying the effect of each scenario is very difficult due to the complex nature of fluvial erosion and geotechnical instabilities. Moreover, the situation becomes more complicated when riverbanks contain cohesive soil. Studies suggested that 10% clay content in a soil structure is sufficient to cause the soil to behave like a cohesive soil (Debnath and Chaudhuri, 2010). Erosion problems on the Red River banks in Winnipeg, Manitoba are therefore complicated due to high clay content in the riverbank material matrix. Riverbank erosion in Winnipeg has accelerated since the 1990s, particularly on the Red River due to a number of spring and summer floods and this has caused an increase in property taxes (Jansen, 2012). Several researchers have conducted slope stability studies on the Red River

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where the main focus was mass slope failure. Baracos and Grham (1981) conducted a study to investigate parameters that affect slope stability on the Red River. Baracos and Lew (2003) suggested that fluvial erosion may impact the slope stability safety factor, and Fernando (2009) conducted a study to quantify the effect of fluvial erosion on the slope stability safety factor. All these studies were focused on slope failures due to geotechnical factors, however there are few studies on fluvial surface erosion due to hydraulic forces in this area. Kimiaghalam et al. (2015) conducted an experimental study to find effective variables on critical shear stress and erosion rate of cohesive riverbanks in Manitoba (including the Red River) due to fluvial surface erosion. Of the 15 different physical, mechanical, and electrochemical soil properties tested, soil cohesion was the best predictor of critical shear stress and erosion rate. Results also indicated that sodium adsorption ratio (SAR) had an effect on erosion rate. The following equations were suggested to estimate the critical shear stress and erosion rate of cohesive Manitoban riverbanks:

$$\tau_c = \alpha C + \beta \tag{1}$$

$$E = f(\mathrm{SAR})(\tau_a - [\alpha C + \beta]) \tag{2}$$

where τ_c is the critical shear stress [Pa], C is the cohesion [kPa], α and β are empirical constants ($\alpha = 0.89$ and $\beta = -0.1$), τ_a [Pa] is the applied shear stress and E [mm/h] is the erosion rate.

Subaerial processes like wetting and drying (change in natural water content) of the soil and seasonal freeze–thaw can affect both fluvial erosion and mass slope failure processes (Thorne, 1982; Lawler et al., 1997, 1999). Lawler (1993) estimated that 32–43% of total bank erosion within the River Ilston in UK was caused by needle ice formation. Yumoto et al. (2006) found 20–60% contribution of subaerial processes on total bank erosion along a small stream in central Japan. Couper and Maddock (2001) suggested that subaerial processes were underestimated on the River Arrow in UK and can have significant impact on erosion. Couper (2003) studied remoulded samples from the River Arrow and found that freeze–thaw cycles had a more significant effect on the riverbank erosion than wetting–drying cycles. Wynn et al. (2008) used a submerged-jet type erosion measurement device to show that critical shear stress and slope of erosion rate varied seasonally, and that erodibility increased with increasing number of freeze–thaw processes in their study area within the Stroubles Creek watershed in Virginia, USA. Seasonal freeze–thaw (FT) can alter cohesive soil behavior; however, due to the different clay minerals in different locations, these changes may not have a similar pattern and quantity. Therefore it is vital to understand the effect of FT processes on local soil in a study area. There is currently no specific study on the effect of FT on riverbank erodibility in Manitoba. Graham and Au (1985) conducted an experimental study to investigate the effect of 5 FT cycles on the stress–strain behavior of Winnipeg clay at low normal stresses. They found a reduction in shear strength after 5 FT cycles. Mixtures of silt and clay are more susceptible than non-cohesive soils to significant negative FT effects (Couper, 2003). In particular, the silt content can control the intensity of these effects because voids between silt particles are small enough to form high capillary forces to move water toward the soil surface where cold air can freeze the pore water between the voids. On the other hand, voids between silt particles are big enough to allow ice lenses to form inside the soil structure. As ice lenses form in the soil structure the frozen water expands and inter-particle bonds become weaker, therefore lower shear strength and critical shear stress are expected after thaw. Still, there is no numerical formulation to predict the behavior of different soils under different FT conditions. The intensity of the effect of freezing and thawing varies with soil texture, moisture, and extent of freezing. Several investigators hypothesised that freezing and thawing increase soil erodibility. Formanek et al. (1984) found that the shear strength of a silt loam was reduced to less than half its original strength after one FT cycle but the second and third cycles resulted in little reduction. Van Klaveren (1987) suggested that the critical shear stress of soil might be half of its initial value after the first cycle. Edwards et al. (1995) found that a mean sediment yield for frozen soil was 25% greater than a similar soil with no freezing history. Van Klaveren and McCool (1998) found that erodibility of thawed soils increased slightly after a single FT cycle. Ferrick and Gatto (2005) performed three experiments with low (16–18%), mid (27–30%), and high (37–40%) water content over different freezing periods and a 24 h thawing period. They found significant increase in erosion rate during runoff with increasing water content. Van Klaveren and McCool (2010) found that when silt loam soil freezes, resistance against erosion increased, but when the thawing process started, the soil surface began to reduce its erosion resistance.

This study focused on flow-induced surface erosion on the Red River bank in Winnipeg, Manitoba, Canada and the effect of seasonal freeze–thaw on this process. The study included field measurements, experimental testing, and numerical simulations to summarize fluvial erosion on the riverbanks for both practical and research purposes. Moreover, this study includes new findings on the effect of several freeze–thaw (FT) processes on the behavior of natural cohesive riverbanks in Winnipeg that would be useful for the design of erosion protection projects.

2. Study area, sampling, and field measurements

The study area was a 10 km reach of the Red River passing through the City of Winnipeg in Western Canada; flowing from the South Perimeter Bridge (49°47′04″N and 97°08′07″W) to the Fort Gary Bridge (49°49′17″N and 97°08′35″W) (Fig. 1). Winnipeg is famous for its harsh winters with an average low temperature of −20.2 °C in winters (The Forks station, Environment Canada). The riverbank consists of a combination of lacustrine clay soils and alluvial deposits. Water elevation can be influenced by the St. Andrews Lock and Dam (50°05′02″N and 96°56′28″W), located 36 km downstream. Water level variation is typically on the order of 6 m annually. Mean annual discharge is 176 $m^3\,s^{-1}$, with peak discharges on the order of 1300 $m^3\,s^{-1}$. At mean flow conditions the average channel top width and water depth are 130 and 3.5 m, respectively. The river is highly sinuous within the city of Winnipeg, and has an average channel bottom drop of 3.8 m per 100 km, with side slopes varying from gradual to steep. Typical midsummer total suspended sediment concentrations are on the order of 121 mg L^{-1}, with peak values on the order of 1500 mg L^{-1} during high flow conditions. Total suspended solids drop to a concentration of approximately 10 mg L^{-1} under a solid ice cover during the winter months (Weiss, 2012).

Eleven soil samples were taken from different locations along the riverbanks. The sampling procedure was to remove the disturbed top soil layer and take vertical samples from the surface of the bank. Samples were collected at least 0.5 m below the bank surface at locations near the water surface that had just recently been exposed to the atmosphere. For this purpose standard ASTM Shelby tubes were used to take relatively undisturbed samples which were essential for this study. To maintain the natural water content, the soil samples were sealed and kept in a refrigerator. Seven soil samples, Red 1 to Red 7, were used to measure the erodibility of natural cohesive riverbanks and the four remaining samples, Red 8 to Red 11, were used to investigate the effects of seasonal freeze–thaw on riverbank erodibility. Samples Red 10 and Red 11 were taken from the same location as Red 1 and Red 2, respectively. Sample Red 7 was taken from freshly deposited,