Evaluating the erosion characteristics of river sediments under varying hydraulic conditions

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ABSTRACT
Increasing river velocity due to flooding causes increased erosion in cohesive soils. This erosion is most aggressive at the deepest portions of the channel and decreases upslope along the channel riverbank. As such the erosion occurring tends to cause over steepening of the riverbank that can ultimately lead to riverbank failure. Due to the interest in understanding the impact of floods of various magnitudes and durations on the stability of natural riverbank slopes an Erosion Measurement Device (EMD) was designed and built at the Geotechnical Laboratory of University of Manitoba in partnership with KGS Group to conduct studies on the erodability of various river sediments. The experiments evaluated the erodibility rate as a function of water velocity so that erosion rate curves could be established for the materials tested under varying sediment load in the eroding water.

RÉSUMÉ
L'augmentation de la vélocité de la rivière causée par des inondations a augmenté l'érosion des sols cohésifs. Cette érosion est plus agressive dans les régions les plus basses d'un chenal et décroit graduellement le long des berges du chenal. En tant que tel, l'érosion tend à causer le retrait des berges pouvant mener à terme à leur disparition. Étant donné l'intérêt de la compréhension de l'impact des inondations de magnitudes et durées diverses sur la stabilité des pentes des berges naturelles, un « Erosion Measurement Device » (Dispositif de Mesure de l'Érosion) a été conçu et développé au laboratoire géotechnique de l'université de Manitoba en partenariat avec KGS Group dans le but de conduire des études sur l'érodabilité de plusieurs sédiments de rivière. Les expériences ont évalué le taux d'érodabilité en fonction de la vélocité de l'eau pour que les courbes du taux d'érosion puisent être définies, pour les matériaux testés, en faisant varier la charge des sédiments dans l'eau érodé.

1 INTRODUCTION

The erosion rate in river channels has long been recognized to be a function of the velocity of flow in the river channel and the characteristics of the channel sediments. In general, the faster the velocity of the water is, the higher the erosion rate. However there is limited measured data that characterizes the erosion rates in cohesive sediments under varying water velocities and sediment load conditions in the eroding water. This information is important in order to characterize the long term erosion rates for river channels in cohesive soils and the potential impact on the stability of the riverbanks.

Significant increases in the water velocity profile due to flooding events can have a notable impact on erosion along riverbanks. The cumulative impacts of multiple events can lead to progressive over steepening of riverbanks and subsequent failure resulting in loss of property for landowners.

An integral part of examining the impact of flooding on riverbank stability is to determine the erodability of typical soils that comprise the riverbanks and river channel. This is a difficult exercise since there are no generally accepted methods to measure the erodability of river sediments in-situ. In order to predict the transient erosion taking place due to varying river levels, the relationship between near bed shear stress and erosion rate must be determined. After establishing this relationship, the erosion of specific riverbank geometries can be estimated using erosion rate functions and water velocity profiles acting on a riverbank cross-section over time.

2 EROSION MEASUREMENT DEVICE

An Erosion Measurement Device (EMD) device has been constructed at the Geotechnical Laboratory at the University of Manitoba based on a device presented by Briaud et al (2000). The device was designed and constructed to test and measure the erodability of cohesive and cohesionless soils and produce an erosion function. This erosion function defines the relationship between the hydraulic shear stress (directly related to flow velocity) applied at the riverbed and the erosion rate for the material.

2.1 The Device

The EMD is a simple device in concept with a flume that passes water over a specimen extruded at set rates into the flow flume. A central water storage tank contains the water required for circulation during testing. The water can be typical tap water or can be mixed to specific suspended sediment load concentrations as required. The pump frequency is regulated and the velocity in the pipe is determined by a flow meter. A central baffle

system and coarse filter prevent large particles from entering the pump and in turn passing into the flume. This may provide more conservative results according to theory and the experiments performed by Merten et al (2001) on erosion in rills. The study confirms larger sediments covering the soil bed during the erosion process shield the soil from flow forces and thus reduce detachment of the soil particles, which would result in lower erosion rates.

Figure 1 demonstrates the end of the flume where the tube with the sample being tested is fastened to the bottom of the flume and extruded with the screw jack.

Figure 1. Extrusion and Erosion Measurement System

2.2 Methodology

A surface roughness of D_{50} of the soil sample was used to determine the shear stress that a certain flow velocity over the sample in the flume would produce. The formula used [1] was obtained from a similar device described by Briaud et al (2000).

$$\tau = \frac{1}{8} f \rho v^2 \qquad [1]$$

Where τ is the shear stress on the wall of the pipe, f is the friction factor obtained from Moody Chart, ρ is the mass density of water (1000 kg/m^3) and v is the mean flow velocity in the pipe.

Each frequency was then set and the average flow velocity in the pipe measured using an ultrasonic flow meter. The velocity in the pipe was converted to the average flow velocity in the flume using the cross sectional area of the two conduits. The flow velocity in the flume was then used to calculate the shear stresses applied to the specimen. From the obtained shear stresses and their corresponding flume velocities, the pipe velocity was calculated and the required frequency to achieve that pipe flow velocity was calculated for the desired shear stresses to be applied to the samples.

A Shelby tube sample was extruded with minimal disturbance to the sample, into the tube fitted for the EMD, using the restriction system on top of the Shelby tube extruder as demonstrated in Figure 2.

Figure 2. Extraction of Sample from Shelby Tube into the tube fitted for the EMD

Initially the flow velocity to produce the desired shear stress on the soil sample was set. Then the erosion was timed and the length of sample that was eroded in that time was measured.

Samples were taken from Shelby tubes and air dried to determine moisture content and grain size distribution. The liquid limit and plastic limit were determined for each sample. A hydrometer test was also performed to determine the grain size distribution of the fines.

In Phase I river water was used and in Phase II sediment was added to tap water to increase the sediment load to desired target levels. The sediments used were predominantly clay sized.

In the test runs it was observed that the sediment load in the water was decreasing while the flow velocities were low and was not causing enough mixing effect in the sump. As a result the water in the sump was mixed via an internal pump to keep the sediment load more consistent.

Some samples were taken from both sides of the sump, after some of the tests and grain size analyses were performed on them, to examine the effect of the weir in the sump.

3 TEST RESULTS

Representative inside and outside bend sites were chosen for this study. The grain size distribution and the erosion rates obtained in the two phases of the tests are presented below.

3.1 Grain Size Analysis

As demonstrated on Figure 3 the inside bend soils had slightly larger particle sizes and slightly lower Plasticity Index, even though their USCS classifications were the same as the outside bend soils. The inside and outside bend samples indicated in Figure 3 had a Plasticity Index of 37% and 43%, respectively.

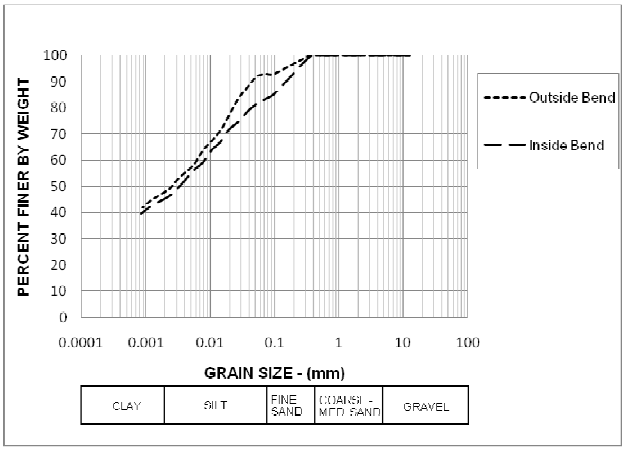

Figure 3. Grain Size Distribution of Inside and Outside Bend Representative Soil Samples

3.2 Phase I Erosion Rates

In Phase I river water was used as the eroding fluid. The samples were tested within the approximate range of 5 Pa to 42 Pa of shear stress.

As can be observed in Figure 4 the outside bend samples had lower erosion rates than the inside bend samples. This was anticipated based on the grain size characteristics of the materials. The inside bend material being coarser alluvial deposits with higher erosion rates and outside bend material finer lacustrine deposits with lower erosion rates.

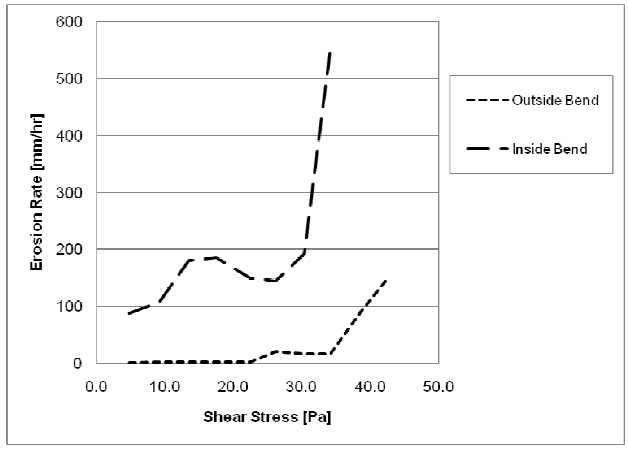

Figure 4. Phase I Erosion Rates vs. Shear Stress of an Inside and Outside Bend Representative Soil Samples

3.3 Phase II Erosion Rates

Three dimensional flow models narrowed the range of shear stress applied to the river banks to 7.5 Pa to 12.5 Pa. Each shear stress was tested at three different sediment loads of zero g/m^3, 100 g/m^3 and 200 g/m^3 to determine the effect of suspended sediments in the eroding water on erosion rate.

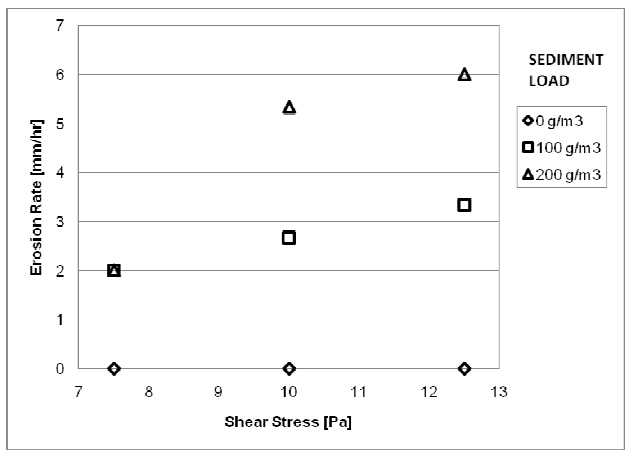

Figure 5. Phase II Erosion Rates vs. Shear Stress with Three Increments of Sediment Load of an Outside Bend Representative Soil Sample

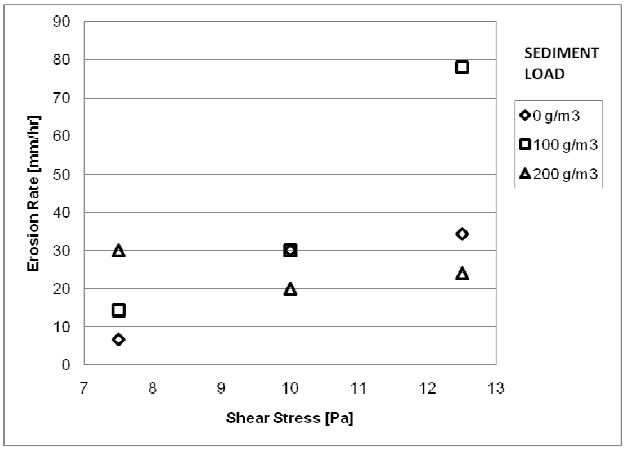

Figure 6. Phase II Erosion Rates vs. Shear Stress with Three Increments of Sediment Load of an Inside Bend Representative Soil Sample

Since the samples were not homogeneous there were some inconsistencies in the erosion rates. The general trend however, as shown in Figures 5 and 6, was that as the sediment load increased, and shear stress increased, the erosion rates also increased.

3.4 Grain Size Analysis of Sump Samples

The eroded materials that were trapped in the sump were also analysed for grain size distribution to determine the effect of the weir and filter in the middle of the sump. Figure 7 demonstrates the distribution of the grain size in the return side and intake side of the sump after testing of one of the most granular samples.

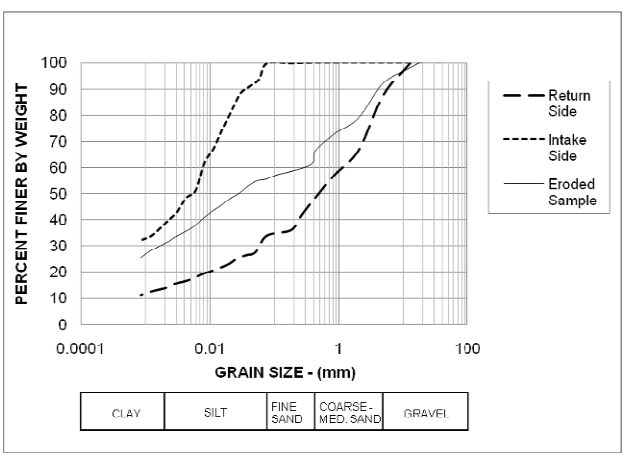

Figure 7. Grain Size Distribution of Return and Intake Sides of the Sump After Testing of a Granular Sample

4 OBSERVATIONS

4.1 Erosion Results

Throughout the testing it was clear that roots and vegetation bound the soil material and reduced the erosion rate. The weaker regions in samples were bubbles and fractures in the samples that also showed accelerated erosion. The soils flaked off during the tests in areas with inclusions present. These were most likely the causes that created fluctuations in the erosion rate graphs, in addition to the sections where the material was less cohesive (i.e. presence of sand seems).

4.2 Sieve and Hydrometer Results

The grain size analyses indicated all specimens were clay with limited varying intermediate plasticity, with grain size distribution approximately similar to each other.

4.3 Atterberg Limits and Unified Soil Classification System

The ranges in moisture content of the samples tested were between 19% and 40%; liquid limits of 56% to 68%; plastic limits of 22% and 26%; and plasticity index of 34% to 43%. The USCS classifications were CI (intermediate plastic clay).

4.4 Phase I of Testing

Throughout the tests the general observation was that a critical shear stress had to be reached to start erosion. As the shear stress increased so did the erosion rate.

4.5 Phase II of Testing

The Phase II observed erosion rates were in general similar to Phase I testing in the same range of shear stresses. Also observed was that in general the erosion rates increased as the sediment load in the eroding water was increased.

The erosion rates of the second phase of testing are generally comparable to the first phase, when compared to the same range of shear stress. Figure 8 demonstrates this for an outside bend representative soil sample. This indicates the same conclusions as the first phase of testing can be made regarding the inside bend material having higher erosion rates.

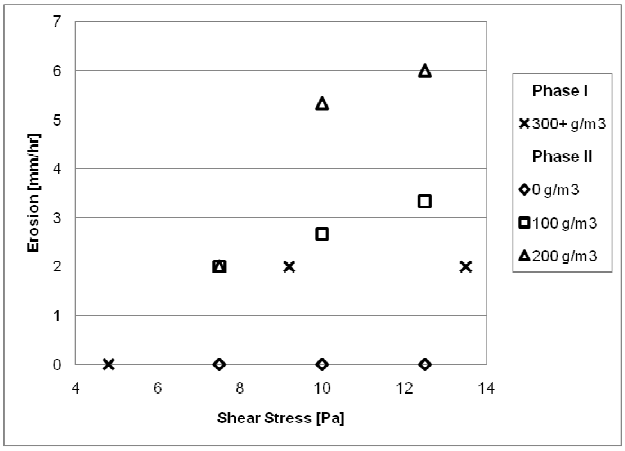

Figure 8. Comparison of Phase I and Phase II Results of an Outside Bend Representative Soil Sample

5 CONCLUSIONS

The results and observations indicate that, as expected, the erosion curves show a similar shape where erosion is limited until a threshold value after which the erosion increases at an increased rate levelling off at what appears to be an asymptotic maximum erosion rate. The threshold erosion level is less in specimens that are less cohesive (inside bend) and the rate of erosion is higher in the more cohesive materials (outside bend). This can be broadly linked to the typical riverbank profiles where alluvial deposits exist more predominantly on inside bends and more cohesive materials on outside bends. However the character of the riverbank sediments at shallow depths that comprised the tube samples show less distinction in index properties.

Even though there were some outliers in the erosion rate graphs due to the non-homogeneity of the samples, the general trend observed throughout the testing was that both increase in velocity/shear stress and increase in sediment load in the eroding fluid increased the erosion rate of the sample.

Some modes of erosion were observed including fracturing and flaking of the soils when there was brown marbling visible, perhaps due to decayed organic matter and/or surrounding larger twigs; and erosion of finer and cohesive soils surrounding larger pebbles until a threshold amount of exposure of the pebble was reached for it to be dislodged.

The results show that, regardless of the material, the erosion rate increased with increasing sediment load and with increasing flow velocity and therefore increasing near bed shear stresses. If a flooding event increases the velocity in the backwater region, then erosion will be accelerated over natural conditions. Conversely, if the event decreases flow velocity in the backwater region, which will also decrease the suspended sediment, then the erosion rate will be reduced from natural conditions. The degree to which the increase or decrease of erosion occurs over natural conditions in the backwater region will depend on the difference in velocity from the flooded to natural conditions. The results obtained from the sites in this study provide a basis for estimating the magnitude of this impact on riverbanks by developing the transient backwater conditions and then integrating the erosion rate curves over the difference in velocity at any given position along the river and through the cross section at that position with respect to time. This is the first measured data of this nature that has allowed, to some degree of certainty, erosion impacts to be examined in a quantitative manner.

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