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Flume tests on fluvial erosion mechanisms in till-bed channels

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Abstract

Semi-alluvial stream channels eroded into till and other glacial sediments are common in areas of extensive glacial deposition such as the Great Lakes region and northern interior plains of North America. The mechanics of erosion and erosional weakness of till results in the dominance of fluvial scour and spontaneous fracture at planes of weakness under shearing flow. There have been few controlled tests looking at erosional mechanisms and resistance of till in river channels. We subjected small blocks of till to unidirectional flows in a laboratory flume to measure the threshold shear stress for erosion and observed the erosion mechanics. Critical shear stress for erosion varied from 7 – 8 Pa for samples with initial saturated moisture content in which a combination of fluvial scour and mass cracking/block erosion dominated. When dried, micro-fissures occurred in the sample and erosional resistance of the till was extremely low at < 1 Pa with erosion appearing to be by fluvial scour. When mobile gravel was added to the test conditions, the gravel reduced the erosion threshold slightly because of the enhanced scour around and below the gravel particles and the tendency for the gravel to aid in crack enlargement. Thus a partial or thin gravel cover over the till may provide no protection from erosion. The erosion processes and effects reflect the complex and contingent mechanics and properties of till, and suggest that the erosion characteristics of till bed semi-alluvial channels differ from abrasion or plucking dominated processes in more resistant bedrock.

Keywords: rivers, geomorphology, semi-alluvial, tills, erosion

Introduction

In depositional landscapes formed by continental ice sheets, such as those in the depositional zone of the Laurentide Ice Sheet of North America, modern river valleys are commonly eroded into glacial sediments rather than into the underlying bedrock (Ashmore and Church, 2001; Gran et al, 2013; Phillips and Desloges, 2014, 2015; Thayer and Ashmore, 2016). These glacial sediments are exposed in river channel boundaries. The glacial deposits vary in composition and origin and include till, glacio-fluvial and glacio-lacustrine sediments. In many cases, especially in till deposits, the material is cohesive but also contains sand and gravel, and may include large clasts up to boulder size even in low relief landscapes. Some of these glacially-derived boundary materials are easily eroded and yield non-cohesive sediments that form local alluvial deposits. Consequently, river banks may include both glacial and alluvial layers, and channel beds may be fully exposed (cohesive) glacial sediments or have a (transient) cover of alluvial deposits varying in extent, thickness and grain size that include rounded clasts of eroded cohesive glacial sediments (Ashmore and Church, 2001, Gran et al., 2013; Thayer and Ashmore, 2016). The combination of non-alluvial (but highly erodible) boundaries and morphological adjustability led Ashmore and Church (2001) to refer to rivers of this type in glaciated landscapes as “semi-alluvial” (see also Meshkova et al, 2011; Khan and Kostaschuk, 2011; Phillips and Desloges, 2014; Thayer and Ashmore, 2016). Although this term has also been used to with resistant bedrock boundaries and partial alluvial cover (Turowski et al., 2008), the two types of channel (bedrock and cohesive glacial sediments) are quite distinct with respect to geomorphic history, morphology (e.g. downstream hydraulic geometry), boundary material mechanics, adjustability to changing flow regime, and erosion processes.

An important practical issue is that semi-alluvial rivers of this type, while constrained by the cohesive boundary materials at moderate flows, are likely to respond to extreme high flows and other exogenic changes in a manner, and at a rate, much like alluvial channels (Ashmore and Church, 2001; Thayer et al, 2016). Predicting these adjustments, mitigating adverse erosion effects from, for example, urbanization, modeling long-term landscape development (Gran et al., 2013) and understanding fluvial history and current influences on river dynamics (Phillips and Desloges, 2015; Thayer et al., 2016), all require greater understanding of the geomorphology of this type of river. A fundamental component is explaining and predicting erodibility and erosion mechanisms of various glacially-derived, cohesive boundary materials.

Recent research on erosion of bedrock in river channels has resulted in significant observational and theoretical advances in understanding fluvial erosion of rock beds (Turowksi, 2012; Whipple et al. 2000, 2013; Hodge, 2017). Erosion mechanisms and resistance vary substantially with rock properties and include mass erosion (block separation and detachment), fluvial scour (hydraulic surface erosion) and micro- and macro-abrasion (Chatanantavet and Parker, 2009). Macro-abrasion is defined as erosion of blocks of bedrock due to particle impacts fracturing the bedrock into pluckable sizes (Chantanantavet and Parker, 2009). Overall resistance to erosion has been shown to relate to bulk properties of the rock such as compressive strength (Stock et al. 2005). Much of the focus of research on long-term fluvial incision into bedrock has been on abrasion mechanisms (Whipple et al, 2013), which are assumed to dominate in most settings where resistance to clear-water fluvial scour is so high as to make it largely ineffective. Observations to date (Kamphuis et al., 1990; Gaskin et al., 2003; Khan and Kostaschuk, 2011, Mier and Garcia, 2011) suggest that for glacial diamicts such as till, fluvial scour and block separationat low stresses are much more effective than in most rock bed channels and this is an important difference in understanding the morphology and development of semi-alluvial channels eroded into glacial deposits.

Variability in composition and structure of till and other glacial diamicts makes the development of general predictions of erodibility difficult. However, analysis of a sufficient range of materials may provide some general empirical guidance and expected ranges of values and behaviour. Erosion testing of glacial sediments has been done using either small intact samples in a laboratory flume or *in situ* jet testing devices. Tests have concentrated on erosion by clear-water fluid stress and by mass erosion, which are assumed to be the dominant mechanisms. Flume tests of minimally disturbed samples of large enough size will include the effect of both hydraulic shear stress and of the structure of the glacial material evident in the mass erosion (due to spontaneous failure at planes of weakness and block formation and detachment) also observed in the field (Kamphuis et al., 1990; Gaskin et al., 2003; Mier and Garcia, 2011). *In situ* jet testing devices overcome the problem of sample damage and modification during removal, but focus only on fluvial scour and do not subject a large enough sample area to shear stress to include the effect of the material's structure on the erosion threshold (Hanson and Cook, 1997; Shugar et al, 2007; Khan and Kostaschuk, 2011).

Surface erosion from fluid shear stress is an important component of erosion of glacial diamicts such as till (Kamphuis et al., 1990; Mier and Garcia, 2011). Surface erosion is known to be one of the major mechanisms of erosion for cohesive sediment, manifesting as smoothing or pitting of the surface (Krone, 1999), and surface erosion of stony till can also reveal embedded gravel and pockets vacated by gravel particles (Mier and Garcia 2011). Flume erosion and jet tests both yield a distinct threshold shear stress for surface erosion and limited testing to date gives threshold stresses that are typically less than 10

Pa (Table 1). The presence of sand or gravel particles in the water column has also been shown to decrease the critical shear stress of a till sample due to abrasion of the sediment and these abrasion effects relative to clear water stress need further assessment (Kamphuis, 1983; Kamphuis et al., 1990). Mass erosion of blocks due to spontaneous fracture at planes of weakness or irregularities in the sediment structure under shearing flow and their subsequent “plucking” by the flow is also an important and distinct erosion mechanism in glacially-derived cohesive material (Gaskin et al., 2003) and may occur with very little applied stress because of the inherent weakness of the material due to its structure. Evidence comes from the presence of fracture and joint planes in till and glacio-marine clays observed as flaking and block separation in the field and in laboratory flume erosion tests (Kamphuis et al., 1990; Gaskin et al., 2003; Mier and Garcia, 2011) with the resulting detached clasts of till or glacio-marine clays lying on the stream bed.

Wetting-drying conditions can have a significant effect on erodibility in this type of material (Gaskin et al., 2003) (as it may also in some types of bedrock (Montgomery, 2004)). Cycles of wetting and drying can greatly increase the erodibility of bank toe sites and frequently exposed channel areas in very short time periods (Shugar et al., 2007). In dried and rewetted samples of Champlain Sea Clays, micro-fissures formed greatly reducing the critical shear stress of the samples (Gaskin et al., 2003). Factors contributing to higher intensity and temporal variability of flows, and hence increasing wetting and drying cycles, such as spring floods, heavy rainstorms, and increased surface runoff due to climate change and urbanization, will all cause increased susceptibility to erosion of cohesive tills and clays compared to alluvial sediments.

Table 1:

Alluvial cover develops on a river bed when the sediment supply to the river channel reach is higher than the capacity of the channel to transport that material (Chatanantavet and Parker, 2008). The cover affects rates of fluvial incision into bedrock as a function of several variables related to channel hydraulics, grain size and bed roughness (Sklar and Dietrich, 2004; Johnson and Whipple, 2007 and Chatanantavet and Parker, 2008; Whipple et al., 2013). An important overall governing relationship in erosion of bedrock channels by abrasion (Sklar and Dietrich, 2004) is the “tools and cover” effect whereby the maximum erosion rate occurs at some intermediate condition between no cover (absence of abrasion tools) and full cover (rock bed is fully protected from abrasion impacts). In till-bed channels, while full cover may protect the bed from erosion, partial or no cover exposes the till to fluvial scour and block separation so that high erosion rates may occur with minimal cover and low bed stress. In this way the erosional conditions for till beds may differ from that for many bedrock channels. In addition, fluvial scour of till yields particles from the diamict in the exposed bed that can contribute to the formation of the cover, and toblock separation. Further studies are needed to elucidate the complex relationship between the gravel particles embedded within the till, the erosion of the till material, and the formation and movement of the alluvial cover. This must involve understanding and predicting erosion susceptibility of till and also the effect of loose gravel cover on till erosion. A long term goal is to develop a mechanistic understanding of erosion and morphological development and response to changes in hydrology and sediment delivery in rivers of this type especially for geomorphic and engineering prediction and design for river stability.

The primary objective of this research, in the analysis of semi-alluvial channel morphology and processes, is to observe erosional mechanisms and define the critical shear stress for erosion of intact till samples from a river incised into cohesive glacial diamict (till) using controlled tests in a laboratory flume. These tests add to the limited evidence base for these types of materials. The tests extend previous observations especially by including the initial observations of the effects of wetting-drying and of gravel cover on erosion processes and susceptibility.

Field Sampling and observations

Intact samples of glacial diamicton (Dorchester Till) were collected in September 2012 from the river bed of Medway Creek, a tributary of the Thames River in London, Ontario (Figure 1). The valley of Medway Creek is eroded into Late Wisconsinan age glacial sediments that are up to 50 m thick overlaying Middle Devonian Dundee Limestone. Beneath the floor of Medway Creek valley, the bedrock is covered by 10-20 m of glacial sediments. Tills in this location are associated with a combination of Erie and Huron lobes of the Laurentide Ice Sheet. The till at lower elevations in the valley is interpreted to be Dorchester Till (Dreimanis et al., 1998) deposited by the Erie Lobe of the Port Bruce Stade (approximately 15000-14000 years B.P. (Licciardi et al., 1999). The Erie Lobe advanced westward along the Lake Erie Basin giving distinctive geochemical provenance. The Dorchester Till is overlain by Tavistock Till, both of which are also interpreted to have affinities with Catfish Creek Till (Whittaker, 1986; Dreimanis et al., 1998). Catfish Creek Till lies directly below the Dorchester Till and may also be exposed in the lower elevations of the Medway valley. These lower tills are overlain by glaciolacustrine sand and silt, above which is Arva Moraine Till deposited by the Huron Lobe advancing from the north, which is capped with glacio-lacustrine silt. This sequence of glacial deposits is exposed in bluffs along the Medway valley (Whittaker, 1986; Dreimanis et al., Figure 4 and Table 2) and the lower tills occur in the river channel bed and banks. The tills contain both local materials derived from older tills and material transported from the source regions of lobes of the Laurentide Ice Sheet to the north and east. Lithological composition of the Dorchester Till gravel component is about 60-75 % limestone and dolostone with over 10% metamorphic rock (Dreimanis et al., 1998), and the matrix (< 63 microns) is 40% carbonate (based on tests using Chittick apparatus quoted in Whittaker, 1986 and Dreimanis et al., 1998). There are no genetic interpretations of the tills (e.g. lodgement versus ablation) but they are assumed to be basal in origin.

Medway River has a catchment area of approximately 200 km ^{2}. Water Survey of Canada has operated a gauging station near the sampling site since 1947 at which the mean annual discharge is 2.8 m^3/s, and maximum daily and instantaneous discharges are 117 and 146 m^3/s respectively. Annual maximum daily mean discharge with 2.3 and 5 year recurrence intervals are approximately 60 and 80 m^3/s. Till is exposed in the bed and banks along the sampled reach and in places is covered by a layer of alluvial gravel-cobble up to 0.3 m thick (Hrytsak, 2012) (Figure 2).

Samples were collected by hand in the form of large blocks of till that had previously been dislodged from the river bed and were resting on the bed submerged in the river. Care was taken to prevent damage to the samples and maintain their initial moisture content during extraction and transport by wrapping them with plastic bubble wrap and cushioning them inside plastic bins. The samples were transported by road to the hydraulics laboratory in Montreal and subsequently stored in a humid room until used (Hydraulics and Geotechnical Laboratories, Civil Engineering, McGill University).

A sample of the gravel cover was collected from the edge of the river to be used in the flume tests. The median particle size (D_{50}) for the 78 collected gravel particles was 23 mm. The study reach has many boulders and large gravel particles which were not collected as they were too large to use in the flume tests. The actual $D_{16,}$ D_{50} and D_{85} values for the reach are14mm, 45 mm and 140 mm respectively, calculated by Hrytsak (2012) (23 mm represents the D_{30}). These were determined from Wolman transects with 100-400 pebbles per sample area for a total of over 4000 pebbles in a reach of about 200 m.

The un-weathered till was very dense and hard both on the bed (under water) and exposed in the bank toe. It could not be penetrated with a shovel by hand and the specific gravity of the samples was later calculated to be an average of 2.36. There is strong field evidence of both mass erosion (block separation and detachment) and hydraulic surface erosion of the till. Observations indicated that the till has natural planes of weakness and defined fractures. In some cases, these fractures were similarly oriented and fracture planes were observed (Figure 3) in the bed and banks. The apparent structure of the material and the abundance of blocks of till on the bed where erosion had taken place was evidence of mass erosion. Mass erosion was also observed as block separation under the water (Figure 4) and mass failure of till blocks from the banks also occurs. The wetting-and-drying cycle weathers the material and increases erosion by causing tension cracks (at a very fine scale) during drying and then a break-down of the cohesive character when re-wetted. This had a visible effect on the banks before and after a short flood event during sampling. Before the flood, the banks down to the water level were dry, cracked and rough on the surface. After the flood, till that had been submerged had a smooth surface, indicative of surface erosion, and the eroded material had slumped down towards the bank toe.

Larger gravel and cobbles could be seen embedded in the till and pockets were visible where embedded particles had been removed. The till is therefore a principle source of the gravel-cobble cover on the bed, in addition to the thin gravel layers in the eroding banks. Loose gravel mantles some areas of the bank toe and a discontinuous gravel-cobble alluvium with occasional boulders covers the river bed (Figure 5). Previous sampling in the reach (Hyrtsak, 2012) showed that 50-70% of the bed area has some cover. In some areas the cover is only one grain thick, but thicker (and finer-grained) bar deposits also occur. Averaged over the reach, gravel cover thickness is 0.3 m (Hrytsak, 2012).

Laboratory tests

Erodibility tests in a hydraulic flume allowed observation of erosion mechanisms in a set-up as close as possible to that in the field with the samples subjected to tangential stresses equivalent to those at the bed of the channel. A 4 m x 0.4 m x 0.15 m recirculating hydraulic flume was used to test the samples (Figure 6).

Discharge was measured with a flow meter placed between the recirculation pump and the upstream tank. Two valves were installed immediately downstream of the pump: the first valve set the flow rate and the second valve allowed for gradual starting and stopping of the flow. The slope of the flume was adjusted over a range of 0.031-0.046 using mechanical jacks at the upstream end of the flume and measured using a surveying level. Bed shear stress, τ_b, was calculated assuming uniform flow as

$$\tau = \gamma RS \tag{1}$$

where γ is the specific weight of water, R is the hydraulic radius and S is the slope of the channel. Flow depth was measured just upstream of the sample using a manual point gauge.

A total of six samples were tested to obtain the critical shear stress: two samples at their initial saturated moisture content, two samples that were air-dried before testing to determine the impacts of wetting and drying, and two samples at their initial saturated moisture content with gravel present in the flow to observe the interaction between the loose gravel and underlying sample. Given the small initial sample masses, only two replicates of each test were possible, resulting in a limitation in our ability to define the magnitude of the uncertainty in the observed critical shear stresses.

Each sample was placed in the flume such that the top surface of the sample was flush with the channel floor. This was achieved by placing the sample on a height-adjustable platform beneath the flume's plexiglass false floor in a 10 cm x 10 cm hole located at a distance of 2.5 m from the upstream end of the channel (Figure 6). The platform was adjusted throughout testing to maintain the erosion surface of the sample level with the flume floor at all times – the frequency of adjustment depended on the erosion rate ranging from seldom to every few minutes.

The samples were prepared for the flume tests by removing them from storage in the humid room and allowing the moisture content of the sample to return to that of the submerged conditions in the river bed by submerging them in water for at least 12 hours. Samples were cut into 0.10 m x 0.10 m blocks with heights varying from 0.07 – 0.10 m, depending on the uncut shape of the till block. A diamond-blade masonry saw allowed for cutting through the large gravel particles in the sample without causing any apparent damage to the sample. To simulate the effect of the till drying between high flow events in the channel, samples 3 and 4 were air-dried in place on the platform in the flume for approximately 48 hours before testing began. Bulk density, specific gravity and particle size distribution were measured using material removed from each sample during sample preparation. The till material was very brittle and clean breaks along pre-existing planes of weakness were common. Consequently the material was handled very carefully and some samples were re-cut prior to testing to ensure that the samples were free from obvious initial cracks. Worm holes were also common and test samples were selected to be free of worm holes on the cut surfaces, however for sample #6 worm holes in the interior of the sample were exposed during testing. The bulk density of the samples ranged from 2490 – 2660 kg/m^3 (2.49 – 2.66 g/cm^3). Moisture content after testing was 10-11% in the samples at the initial saturated moisture content and 23-24% in the pre-dried samples (tests 3 and 4). Particle size distributions indicated 8% gravel within a fine matrix of 20% sand, 29% silt and 43% clay (International Wentworth scale).

Each sample was placed in the flume and subjected to a unidirectional current (supercritical flow) applying a uniform shear stress to the surface of the material. The shear stress on the sample was increased incrementally (0.5-1.0 Pa) by increasing the flow rate and erosional effects at each applied shear stress were observed. The critical shear stress was taken as the shear stress at which erosion was first visible. At each given shear stress (flow rate), if no erosion was apparent after 15 minutes, or if erosion ceased, the shear stress (flow rate) was then increased. Testing stopped after the sample had either been eroded completely, if it had been subjected to the highest possible shear stress (approximately 8.9 Pa), or if all erosion had ceased. Observations and pictures were taken at each applied shear stress to determine the critical shear stress and to describe the erosion process.

Samples 5 and 6 were tested to observe the interaction between the loose gravel cover and the erosion of the cohesive till. The gravel was placed in the flume upstream of the till sample and a collection cage was used at the downstream end of the flume to collect the transported gravel particles. Gravel particles collected downstream were transferred upstream to maintain a continuous supply of gravel during testing.

Erosion test results

The critical shear stress values for the six samples obtained from the hydraulic flume studies are summarized in Figure 7. Critical shear stress ranged from 0.9 – 8.3 Pa. (Table 2). Critical shear stress was almost an order of magnitude lower for the two air-dried samples (3 and 4) compared to the samples at the initial saturated moisture content, and the presence of loose gravel moving over the till reduced critical shear stress slightly compared to the absence of gravel. The plot of applied stress over time for samples 5 and 6 reflects the fact that at times the samples were completely covered by gravel and it was assumed that stress on the till surface was effectively zero under those conditions.

Table 2

Samples 1 and 2 showed similar erosion behaviour (Fig 8). Sample 1 eroded by a mass erosion process in which spontaneous fracturing delineated small blocks of till, which eventually detached from the sample. The first sign of weakening of the till sample was a crack developing down the middle of the sample at an applied shear stress of 6.7 Pa, appearing to split the entire sample in half. With a further increase in the applied shear stress to 7.9 Pa, a block of till adjacent to the crack became detached and eroded - this point was assumed to be the critical shear stress of the sample. Further increase in the critical shear stress did not yield more mass erosion (block separation and detachment), however, embedded gravel pieces within the surface of the sample were slowly revealed as fluvial scour (surface erosion) of the clay matrix occurred. In Sample 2, very small gravel pieces were eroded from the surface of the sample by first becoming more exposed by surface erosion of the matrix and then being plucked from the surface at a shear stress of 6.7 Pa. With a further increase to 7.6 Pa, cracks began forming at the surface, including a large crack originating from a large gravel piece and extending to the edge of the sample. At 8.3 Pa, blocks of till began detaching from the cracked areas, and this was taken to be the critical shear stress of the sample. As the applied shear stress increased to 8.8 Pa, more large cracks formed along the surface and the sample continued to undergo mass erosion (block separation and detachment).

Erosion of the air-dried samples (3 and 4) occurred by fluvial scour/surface erosion as soon as the sample was subjected to flow at the minimum shear stress of 1.2 and 0.9 Pa for both samples. Surface erosion began immediately at the edges of the sample and around large gravel particles embedded in the sample. Gravel particles detached from the sample when they became fully exposed. On sample 4, erosion also occurred by removal of very small pieces of the fine-grained matrix. Within 30 minutes both samples had lost a large proportion of their initial mass (Fig 9). Erosion of the air-dried samples was effectively by disintegration of the sample into sub millimeter particles delineated by the microfissures, the larger scale mass failure and cracking seen in the initial moisture content samples did not occur The observed moisture content of the air-dried sample after testing (a mass of very small particles) had increased to 23-24% (compared to 10-11% of the initial water content sample) due to the microfissures resulting in a higher surface area and allowing for increased absorption of water. These observations show that wetting and drying has a substantial effect on the erosional resistance, as seen in a comparison of Figures 8 and 9.

Samples 5 and 6 were tested with mobile gravel particles in the flow to obtain an initial understanding of the effect on till erosion of rolling particles and of a gravel cover layer in protecting the till from hydraulic erosion. The gravel particles were initially placed upstream of the sample. As the flow rate and applied shear stress were increased, the gravel particles moved to cover the sample, and then eventually began rolling downstream (at velocities much lower than the flow velocity), causing damage to the sample surface and initiating mass erosion (block separation and detachment).

In test 5, when the applied shear stress was increased to approximately 3-4 Pa, the gravel particles moved downstream and covered the sample. Erosion could not be observed while the gravel particles covered the sample. When the average applied shear stress was increased to approximately 5 Pa, the gravel particles moved a small amount on the sample causing damage to the corners of the sample. When the average applied shear stress increased to 6.8 Pa, the gravel particles started rolling down the flume. At this point mass erosion (block separation and detachment) started and this was taken to be the critical shear stress. Block separation and detachment occurred at the downstream corner of the sample due to cracks caused by impacts from the gravel particles and from enlargement of cracks. The presence of the gravel particles also caused a noticeable increase in surface erosion by first pitting and subsequently smoothing the surface compared to clear water conditions. The upstream side of the sample 5 underwent more erosion than the downstream side.

Sample 6 showed similar effects, including erosion of the till while it was covered with gravel (Fig 10), which occurred at shear stresses below 7.9 Pa. At higher stresses the rolling gravel caused the sample to erode more quickly by first cracking, the cracks delineating blocks, and finally separation and detachment of the blocks in a mass erosion process. Blocks detaching from the sample caused irregularities in the surface of the sample that was subsequently smoothed by the gravel particles. The shear stress versus time trajectory for samples 5 and 6 has gaps as shear stress values on the till surface were unknown due to the presence of the gravel. The gravel increased the flow depth, channeled the flow and/or protected the till from exposure to the shear stress. Static gravel cover may aid erosion by increasing turbulence, and mobile particles affectboth mass erosion as block separation and detachment of the material and surface erosion by particle impacts..

Discussion

The field observations and flume tests performed on the till samples of Medway Creek exposed the natural structure of the till and demonstrated that mass erosion as block separation and detachment is the dominant erosion mechanism, although surface erosion due to fluvial scour also occurs. The structure of the material, as termed by Lefebvre et al. (1985), was readily apparent in the field, and in the handling and testing of the material. Fractures could develop in the sample where there was no apparent origin, indicative of an existing plane of weakness within the sample, or near gravel particles embedded in the sample. These observations are similar to those from some previous studies (Kamphuis et al.,1990, Mier and Garcia,2011, Gaskin et al., 2003, Lefebvre et al. 1985) in which the till or clay was eroded by blocks of material first being delineated by fractures, at planes of weakness or close to discontinuities, and subsequently detaching from the sample. However, erosion is not immediate once critical shear stresses are achieved because actual detachment is preceded by a phase of fracturing. The erosion proceeded as described in previous studies (Kamphuis et al. 1990; Gaskin et al. 2003; Mier and Garcia, 2011). At the a given shear stress, cracks formed spontaneously, then slowly widened over time, leading to the delineation of blocks of till followed by mass erosion through separation and detachment of the blocks. The initial fracturing of the sample would happen quickly, but most of the erosion occurred as block detachment after a relatively long delay related to crack propagation and widening. There was only one phase of crack propagation and separation and detachment of blocks after which erosion ceased at a given shear stress.

While mass erosion, defined as block separation and detachment, was the dominant erosion process in the till, surface erosion due to fluvial scour had an important role. In the flume studies, small gravel particles detached from the surface after first becoming exposed due to a lowering of the till surface by fluvial scour, similar to the surface erosion observed by Mier and Garcia (2011). New irregularities in the sample surface could become locations for initiation of block separation and detachment. The amount of surface erosion that occurred was less than a centimeter, but it played a significant role in exposing gravel pieces. The distribution of particle sizes within till material influences the erosion – the silts and clays are responsible for its cohesive nature and the larger particles supply the alluvial cover. The full particle size distribution was not available as the small size of the sample precluded sampling the larger gravels and boulders.

The critical shear stress value for till at its initial saturated moisture content with clear flow conditions was determined to be approximately 8 Pa, which is higher than values in previous tests. Kamphuis et al. (1990) and Mier and Garcia (2011) both found lower critical shear stress values (0.65-4.1 Pa for Kamphuis et al. (1990) and 4.2 Pa for Mier and Garcia (2011)) for their tested clay and till samples, with two of the samples by Kamphuis et al. (1990) an order of magnitude less. The difference could be due to the wide variation of clay and till properties(size distribution). However, the critical shear stress values are within the range of values determined by Gaskin et al. (2003) for Champlain Sea clay, albeit a wide range was observed.

Although the critical shear stress values from the two *in situ* jet-tester studies (Shugar et al., 2007; Khan and Kostaschuk, 2011) are similar in magnitude, there are reasons to question the reliability of this type of test. The critical shear stress in those tests was determined by the flow conditions at the time when the first block of material detached from the sample. As discussed above, mass erosion through block separation and detachment is due to the structure of the cohesive material matrix and irregularities in the surface. Therefore, tests that do not allow the full progression of erosion to occur, such as jet testers, will not get an accurate representation of the critical shear stress. The flume tests more accurately represented real flood conditions by having a flow rate, and thus, shear stress value, that slowly increased over time, making the obtained critical shear stress values more reliable. In addition, the area of the sample eroded by the jet testers is smaller than that needed to allow for mass erosion through block separation and detachment and hence to observe the mass erosion of sample due to its structure. Further limitations of the jet test are inherent in its design. The basic principle of the jet tester method is that the incident jet stress is converted to a tangential stress on the surface to yield an erodibility value (Hanson and Cook 1997). In some cases the jet test tends to drill a hole in the surface so does not directly assess shear stress on the surface of the material (Khan and Kostaschuk, 2011). Additionally, after each measurement, the operator must remove large particles, or gravel pieces, in the test hole to accurately assess the maximum erosion depth from which threshold shear stress is calculated (Shugar et al. 2007). Abrasion due to particles trapped in the hole during the test could also affect the results. Results from jet testing of till erosion in southern Ontario rivers have given highly variable (5 orders of magnitude) values for the threshold shear stress (Shugar et al., 2007; Khan and Kostaschuk, 2011), which may also be a reason to question its reliability. Consequently, flume tests which better reproduce conditions in the channel and dominant erosion mechanisms are preferred to *in situ* jet testing for this type of material.

Physical weathering by air-drying of the sample has a dramatic effect on critical shear stress and extreme effects on the erosion process. With drying, the critical shear stress was reduced from 8 Pa to less than 1 Pa, in agreement with the Gaskin et al. (2003) study on the effect of drying Champlain Sea clay. There were no visible cracks within the sample during or after the drying process, however micro-fissures formed within the sample. This was evident when flume testing began and erosion occurred quickly in the form of very small pieces of till flaking away from the surface. Micro-fissuring was apparent along the dried banks of the river on the Medway Creek field site, which penetrated up to 15 cm. It was clear from the final texture of the material after flume testing that the samples had lost their cohesive structure during drying and evident in the subsequent wetting by the flow (weathering). This is in agreement with the study by Govers and Loch (1992) in which lower initial water content led to more micro-fissuring and less resistance to erosion due to a weakening of the cohesive nature of the material. The extreme effects that drying has on the erodibility of till put the lower banks of till rivers at the greatest risk of erosion. These areas are exposed to the most frequent wetting-and-drying cycles from changing river stage. More frequent wetting-drying cycles, for example in urban runoff regimes, would exacerbate this risk. This is clearly an important effect that does not affect erosion in channels in resistant bedrock and therefore an important difference to be considered in developing erosion theory and models for glacial diamicts and similar materials.

The presence of alluvial gravel during laboratory flume tests increased the erosion of the till sample, and decreased the critical shear stress slightly from about 8 Pa to less than 7 Pa. The impacts from the gravel particles eroded the till sample whose surface was subsequently smoothed by fluvial scour. The gravel particles also caused considerable turbulence while they were on top of the sample, and in some cases this caused additional hydraulic erosion. In the context of the river bed, as till is eroded at higher bed shear stress, more gravel particles will be released from the till and potentially enhance erosion of the till if gravel cover is thin. In the case of till, the erosional influence of the extent of alluvial cover may be different in some respects from that observed particularly for abrasion-dominated bedrock cases (Sklar and Dietrich, 2004; Johnson and Whipple 2007). In the absence of cover direct fluvial scour causes rapid erosion even at very low bed stresses. Erosion of the till itself yields low-velocity, saltating particles that may contribute to bed erosion. The wetting-drying behaviour adds another complexity to predicting erosion mechanisms and rates in this type of channel.

Conclusions

Flume erosion tests of glacial diamict (till) taken from the channel of Medway Creek, Ontario, Canada, has extended previous observations of fluvial erosion mechanisms and erosion resistance in this type of material. Critical shear stress for erosion was determined to be approximately 8 Pa. This value is greatly reduced when the material is subjected to physical weathering in the form of wetting-and-drying. Air-dried samples were determined to have a critical shear stress < 1 Pa. The till material had an internal structure, which led to mass erosion by block separation and detachment to be the dominant form of erosion. Block separation and detachment initiated around irregularities and planes of weakness within the internal structure, and could also originate at embedded gravel particles. The presence of an alluvial cover in the form of a single layer of gravel particles lowered the critical shear stress value to less than 7 Pa. Saltating gravel particles impacted the sample and created areas of weakness for increased erosion to take place causing both incision and smoothing of the surface. When the gravel particles remained stationary and covered the till, turbulence around the gravel created localized high areas of shear stress which eroded the sample beneath the gravel. Clearly till-bed channels are extremely erodible and the presence of thin gravel cover over the till may enhance rather than protect the bed from erosion. Because of the nature of the erosion mechanism, direct flume testing of samples is preferred to *in situ* jet testing of erodibility of glacial diamicts. Erosion mechanisms and the role of alluvial cover differ significantly from typical bedrock channels and consequently existing models of bedrock erosion mechanics and incision are not transferable to analysis of rivers eroded into cohesive glacial sediments such as till. Channel design and geomorphic engineering for erosion mitigation must also take these characteristics into account.

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Table 1: Critical shear stress of undisturbed samples of tills and clays

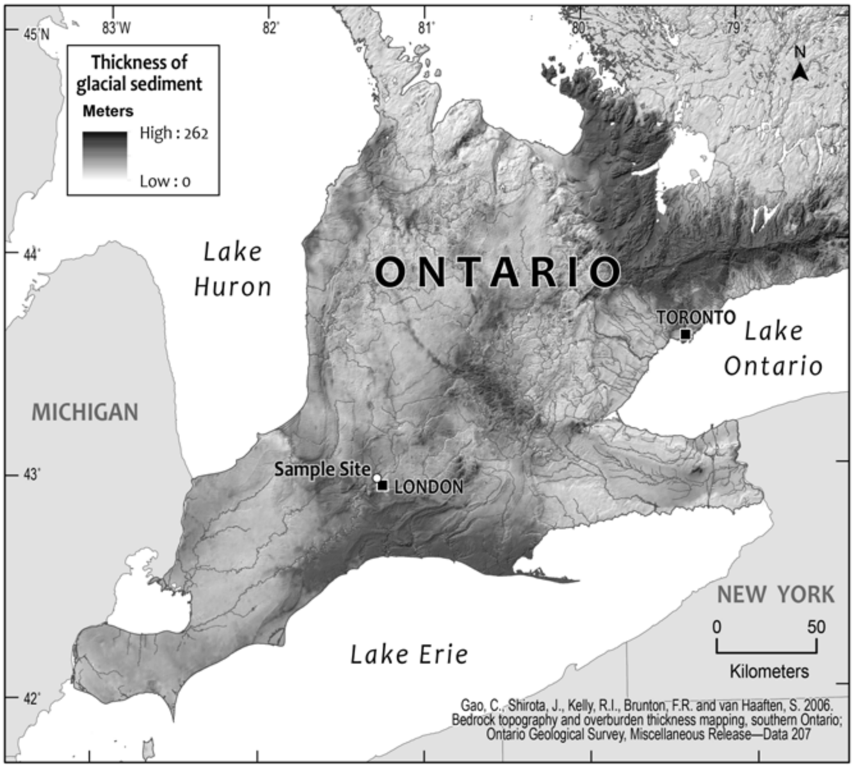
Study	Apparatus	Material	Average Critical Shear Stress (Pa)
Kamphuis et al. (1990)	Flume	Silty Clay	2.56 – 4.1
		Glaciolacustrine Silty Clay	0.88
		Silty Till	0.65
Gaskin et al. (2003)	Flume	Champlain Sea Clay (St. Lawrence River) Initial saturated moisture content	6 – 20
		Air dried sample	<< 5
Mier and Garcia (2011)	Flume	St. Joseph'sTill (St. Clair River)	4.2
Shugar et al. (2007)	*in situ* Jet-Tester	Halton Till (Fletcher's Creek)	2.28
Khan and Kostachuck (2011)	*in situ* Jet-Tester	Halton Till (Fletcher's Creek)	5.43
		Sunnybrook Till (Highland Creek)	22.7

Table 2: Critical shear stress from flume tests of till samples from Medway Creek

Sample	Test Description	Critical Shear Stress (Pa)
1	Initial saturated moisture content clear water flow	6.9
2	Initial saturated moisture content clear water flow	8.3
3	Air dried, clear water flow	1.4
4	Air dried, clear water flow	0.9
5	Initial saturated moisture content Gravel in flow	6.8
6	Initial saturated moisture content Gravel in flow	4.3 – 6.1

Figures and captions

Fig 1	Field site location (Medway Creek) and thickness of glacial overburden in southern Ontario (source: Ontario Geological Survey)
Fig 2	a) Medway Creek bank showing till in lower bank with overlying sand and gravel b) Till at base of bank extending across the bed below the water
Fig 3	a) Till in lower bank showing fissures and embedded gravel particles b) Eroded till blocks at edge of channel c) Fracture and failure of till in banks
Fig 4	a) Till exposed in the channel bed with indications of erosion by fluvial scour and block separation b) Close up view of mass erosion (block separation and detachment) of till on channel bed
Fig 5	a) Overview of channel showing exposed till (light patches) and thin gravel cover layer b) Close up view of till patch exposed beneath gravel cover
Fig 6	a) Plan view of flume and sample location b) Photo of flume photo showing block placement
Fig 7	Flume erosion test results of the applied shear stress versus time (—, ····, ---) and the critical shear stress (✱,**O, Δ**) for each sample type: initial saturated moisture content, air dried and initial saturated moisture content with gravel abrasion.
Fig 8	Sample 2, initial saturated moisture content clear water flow, a) before and b) after erosion test top view, c) before and d) after erosion test side view.
Fig 9	Sample 4, air dried clear water flow, a) before and b) after erosion test
Fig 10	Sample 6, initial saturated moisture content gravel abrasion, a) before and b) after erosion test



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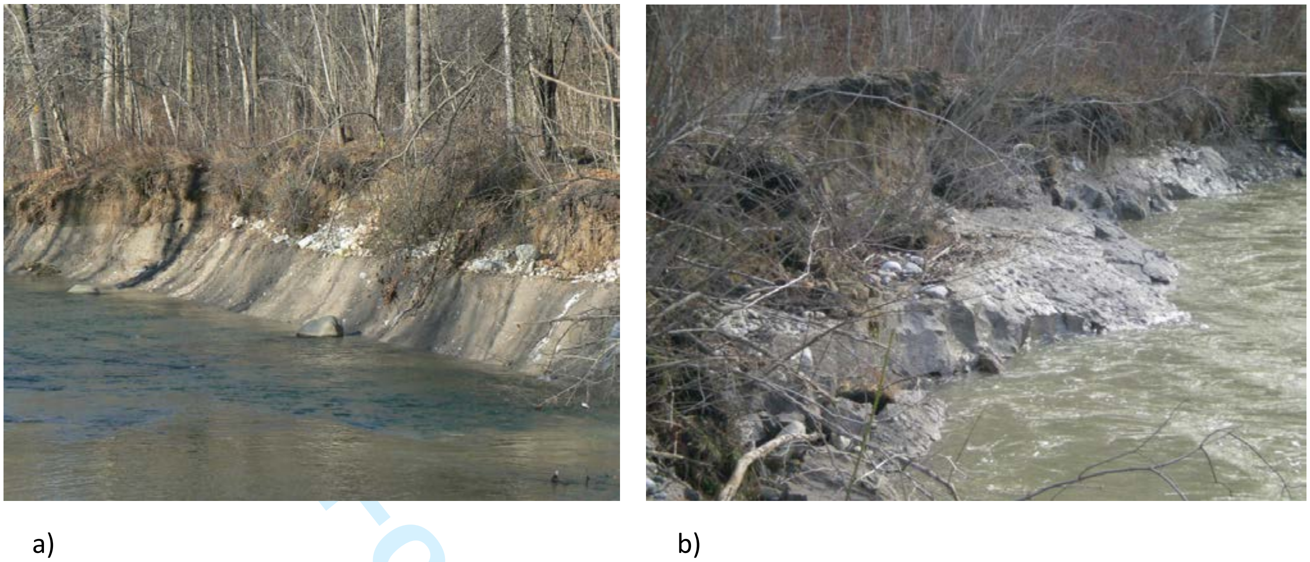

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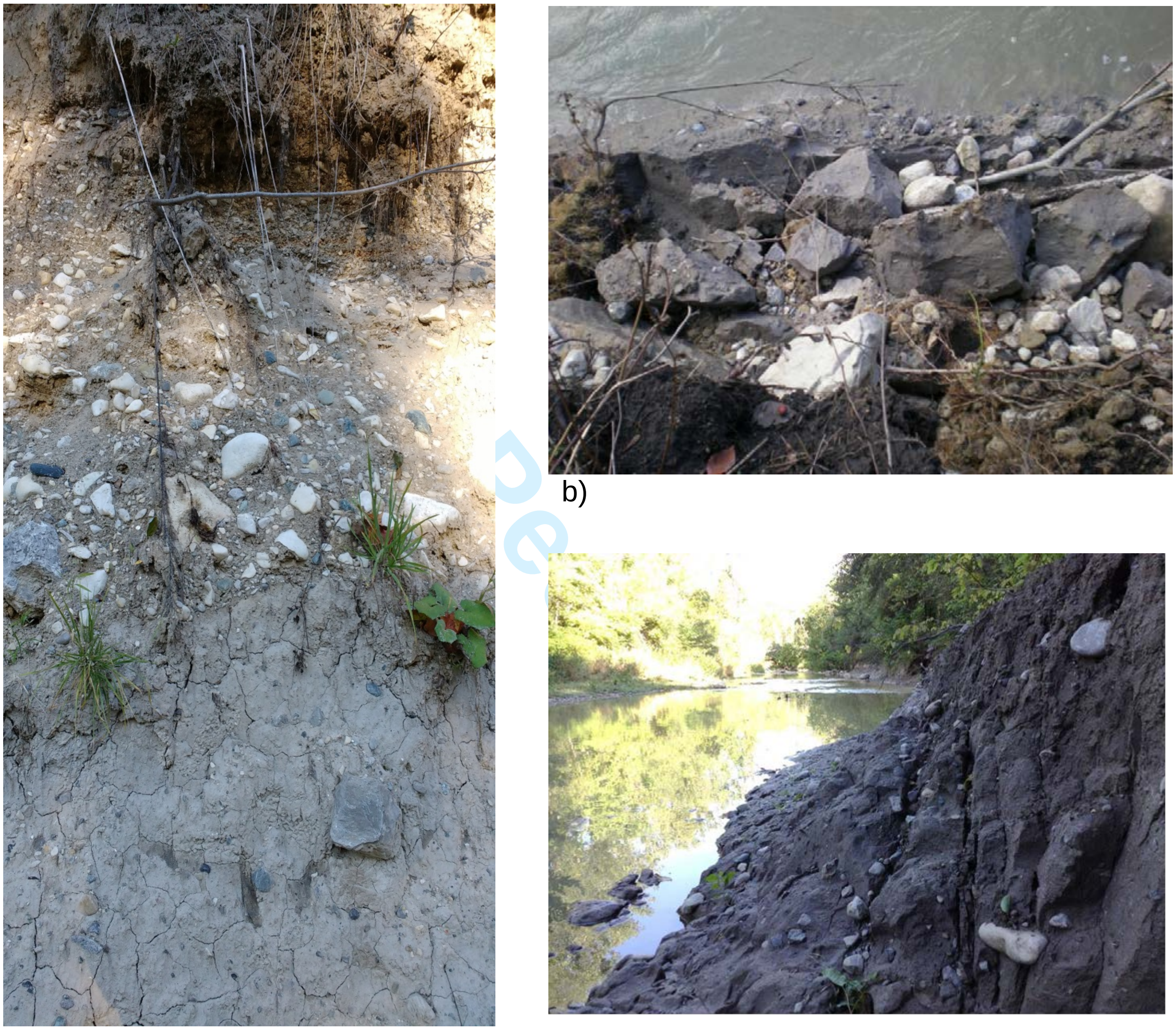
b) Till at base of bank extending across the bed below the water



b)

a)

c)

Figure 3 a) Till in lower bank showing fissures and embedded gravel particles
b) Eroded till blocks at edge of channel
c) Fracture and failure of till in banks

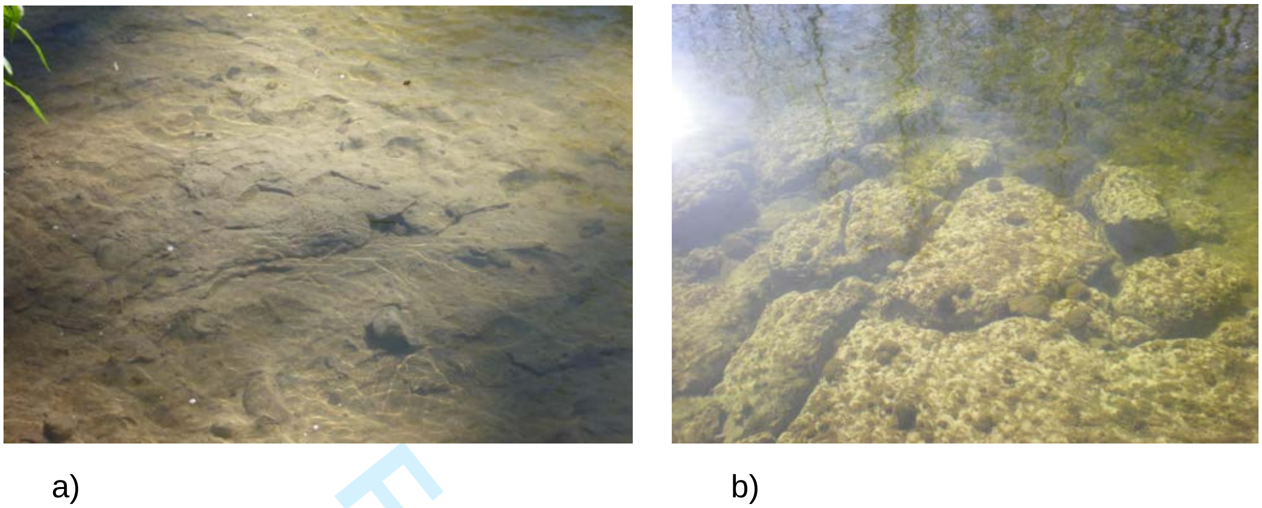


Figure 4 a) Till exposed in the channel bed with indications of erosion by fluvial scour and block separation
b) Close up view of mass erosion of till on channel bed

a)

b)

Figure 5 a) Overview of channel showing exposed till (light patches) and thin gravel cover layer (Photo by Tatiana Hyrtsak)
b) Close up view of till patch exposed beneath gravel cover

b)

Figure 6 a) Plan view of flume and sample location
b) Photo of flume photo showing block placement

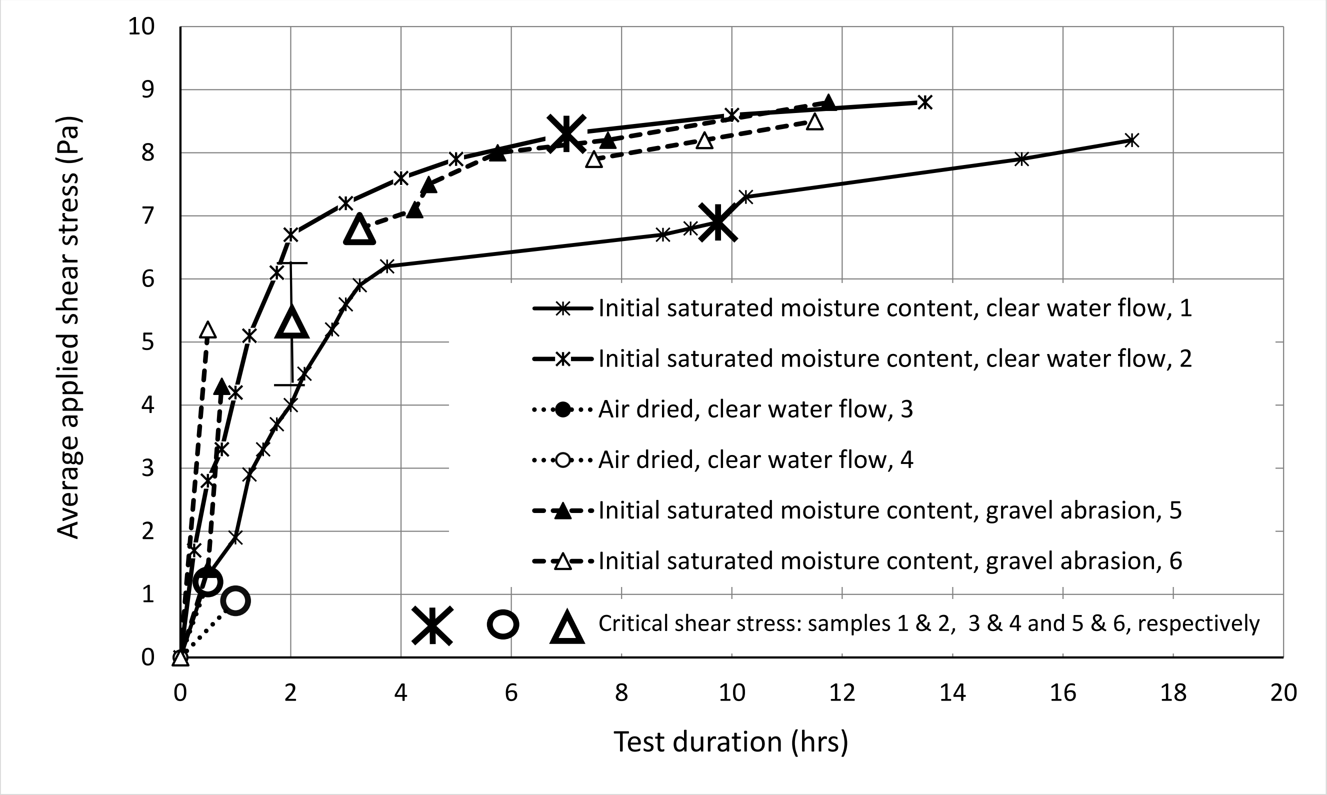
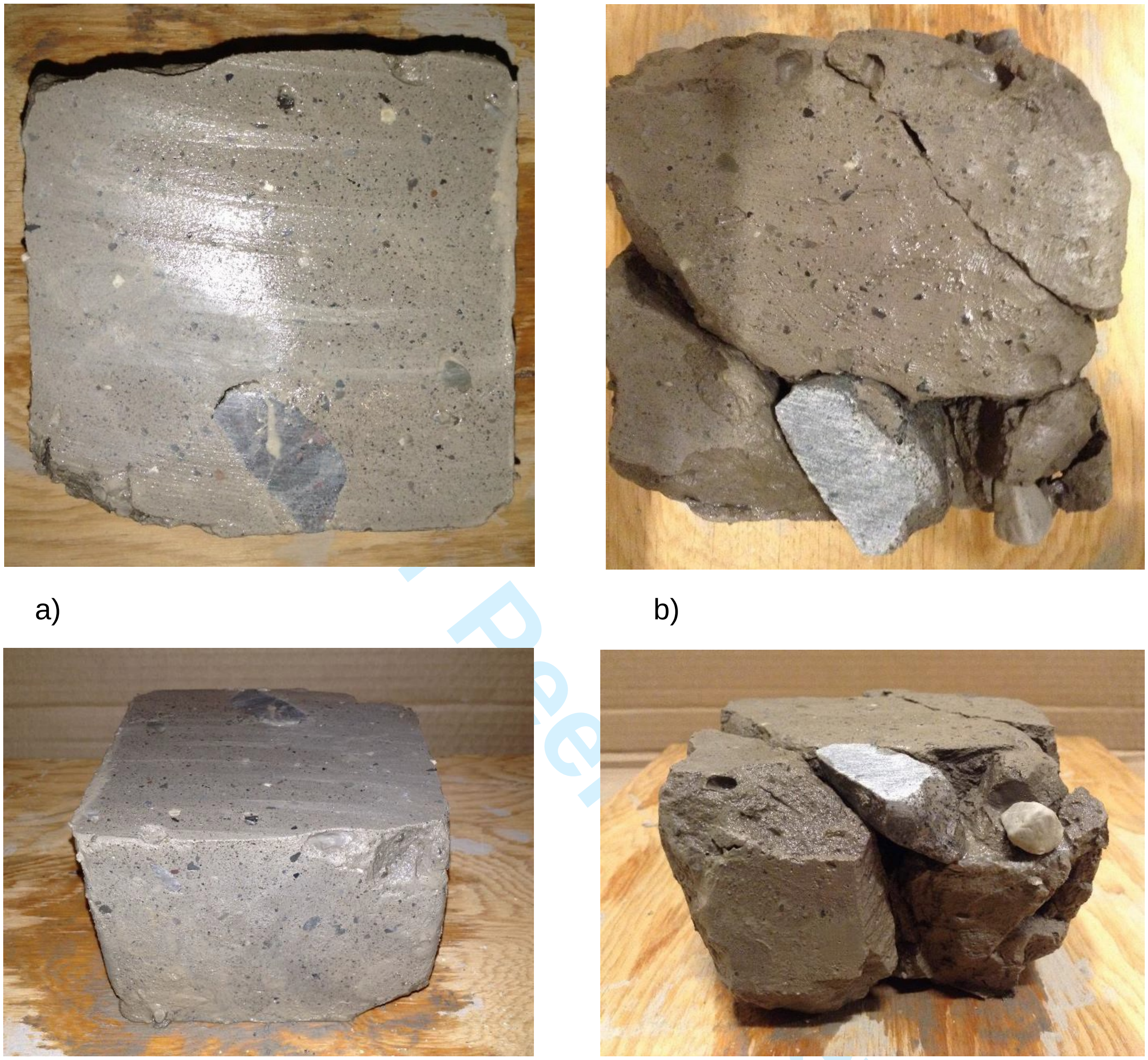


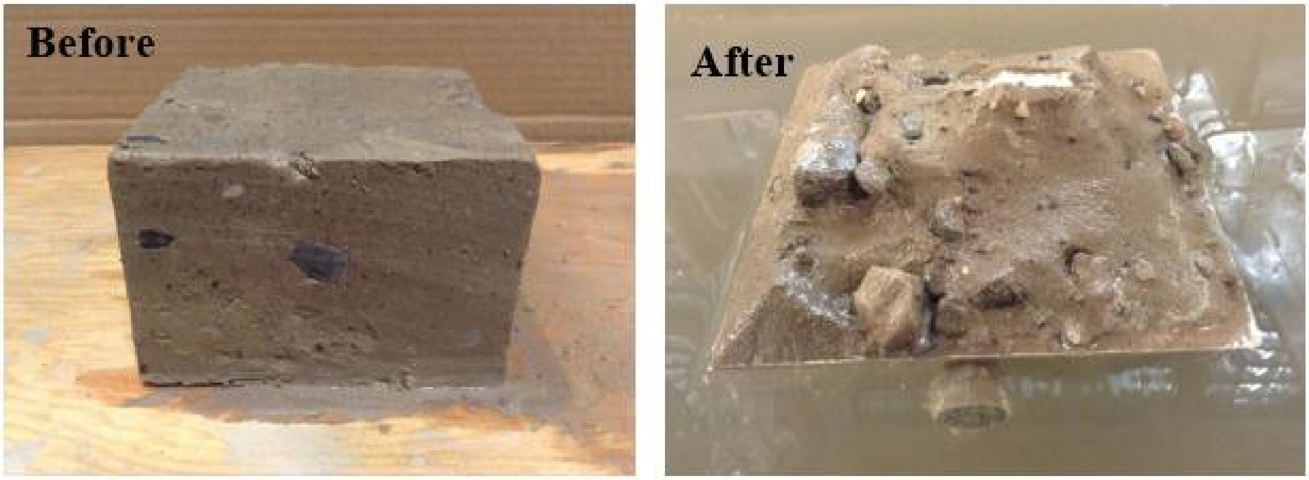
Figure 7. Flume erosion test results of the applied shear stress versus time (—, ····, ---) and the critical shear stress (✱, **O, Δ**) for each sample type: initial saturated moisture content, air dried and initial saturated moisture content with gravel abrasion.



a) b)

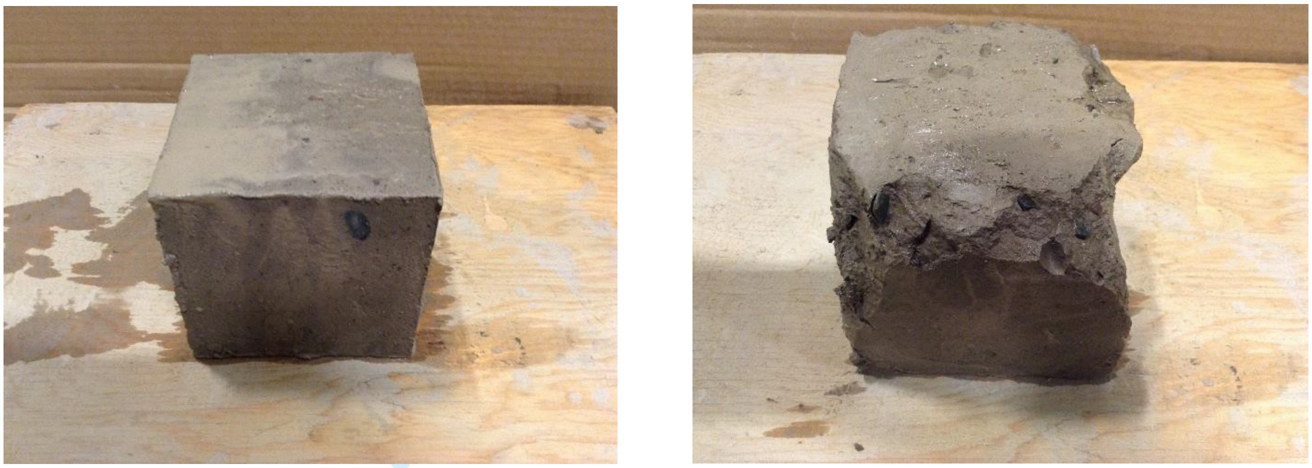
c) d)

Figure 8 Sample 2, initial saturated moisture content clear water flow, a) before and b) after erosion test top view, and c) before and d) after erosion test side view.



a) b)

Figure 9 Sample 4, air dried clear water flow, a) before and b) after erosion test



a) b)

Figure 10 Samples 6, initial saturated moisture content gravel abrasion, a) before and b) after erosion test