Armourstone Revetments – will standard design criteria prevent failure?

By

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Abstract

Bank stabilization structures are used to prevent the loss of valuable land within the urban environment and the decision for the type of structure used depends on the properties of the stream. In the urban areas of Southern Ontario there is a preference for the use of armourstone blocks as bank stabilization. The armourstone revetment is a free standing stone structure with large blocks of stone layered vertically and offset from one another. During fieldwork at Forty Mile Creek in Grimsby, Ontario armourstone failure was identified by the removal of two stones within one column from the wall. Since the footer stones were still in place, toe scour was eliminated as a cause of failure.

Through theoretical, field, and experimental work the process of suction has been identified as a mode of failure for the armourstone wall and the process of suction works similarly to quarrying large blocks of rock off bedrock streambeds. The theory of lateral suction has previously not been taken into consideration for the design of these walls. The physical and hydraulic evidence found in the field and studied during experimental work indicate that the armourstone wall is vulnerable to the process of suction.

The forces exerted by the flow and the resistance of the block determine the stability of the armourstone block within the wall. The design of the armourstone wall, high surface velocities, and short pulses of faster flowing water within the profile could contribute to armourstone failure by providing the forces needed for suction to occur, therefore adjustments to the design of the wall should be made in order to limit the effect.

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List of Symbols		**Dimensions**
A_f	area of block perpendicular to flow	m^2
A_p	area of block parallel to the flow	m^2
C_I	coefficient for isolated or embedded stones used in the Isbash equation (Carling and Tinkler, 1998)	
C_D	drag coefficient	
C_L	lift coefficient	
d	flow depth	m
Dc	stone size	m
F_D	drag force	Newtons
F_F	friction force	Newtons
F_L	lift force	Newtons
F_N	buoyant weight of the block	kg/m^3
F_R	the resultant force of F_N and F_L acting normal to the surface	Newtons
Fr	Froude number	
H	height of water in corner block tubes	m
H_v	velocity head	m/sec
g	gravitational constant	m/sec^2
L	distance	m
L_{32}	Sauter mean (for scallop analysis)	cm
ℓ_i	lengths of individual scallops in a homogeneous population	cm
n	Manning's roughness coefficient	
P	pressure	$Newtons/m^2$
ρ_r	mass density of rock	kg/m^3
ρ_w	density of water	kg/m^3
PS_m	partial submerged mass	kg/m^3
R_R	Rock Resistance	Newtons
S	Suction Force	Newtons
S_{chan}	slope	
s_{crit}	critical slope	
S_m	submerged mass	kg/m^3
S_R	Stability Ratio	
T	time	seconds
μ_f	coefficient of friction	
μ_s	coefficient of suction	
V	mean flow velocity	m/sec
V_s	mean surface velocity	m/sec
V_t	threshold velocity for block movement	m/sec
v_t	total velocity	cm/sec
$V*$	shear velocity	m/sec
w	wavelength	m
x	the length of the block that is parallel to the main flow	m
y	the length of the block that is horizontally perpendicular to x	m

z	the vertical length of the block	m
X	orthogonal direction parallel to flow, measured from ADV	
Y	orthogonal direction perpendicular to flow, measured from ADV	
Z	orthogonal direction vertical, measured from ADV	
γ	specific weight of a fluid (density times gravitational constant)	Newtons

Chapter 1 – Introduction

1.1 Purpose

In populated areas of Southern Ontario, it is easy to find a stream that has been impacted by urbanization. In the urban areas of Southern Ontario there is a preference for the use of armourstone blocks for bank stabilization, possibly due to its natural appearance, availability of the stone, and its apparent structural integrity. The purpose of this thesis is to illustrate a failure mechanism for armourstone revetments that previously has not been taken into consideration. Through theoretical, field, and experimental work the process of suction has been identified as either a primary or contributing cause to armourstone revetment failure.

1.2 Design of the Armourstone Wall and Modes of Failure

Specific design standards for armourstone revetments were difficult to locate and it appears that bank stabilization work has been done using general engineering principles. The only standard found was from the Maryland Department of the Environment Water Management Administration (2000) which was very precise in the sense that it gave details on the materials used and the design layout. There were no Canadian standards for armourstone revetments found during research, so the Maryland standard (2000) was used to compare seven armourstone walls within the urban areas of Southern Ontario to investigate if there were any similarities or differences in the design of these walls.

Structural failure of armourstone walls was noticed in the majority of the streams studied during the fieldwork phase of this project. In much of Southern Ontario, the streambeds consist of weak shale which is easily eroded due to the process of wetting and drying which can cause problems for the stability of the armourstone revetment because the stones are typically lying on top of the bedrock. Once the shale has been eroded the base stone loses its support and the stone slumps toward the stream, eventually being

entirely removed from the wall. During fieldwork at Forty Mile Creek in Grimsby, Ontario armourstone failure occurred when two stones within one column were removed. The failure that occurred here was different due to the fact that the footer stones were still in place and the surrounding stones had not been impacted by scour, indicating that there must be another cause of failure.

1.3 Field and Experimental Research

The stability of the armourstone wall depends on the whether the blocks remain in their initial position. Hydraulic equations can be used by engineers to determine the size of rock used in bank stabilization but are based on criteria controlling movement of isolated rocks within the channel. These criteria are not necessarily applicable to the hydraulic conditions that influence movement of a rock out of a wall.

The only apparent cause of failure for the armourstone wall at Forty Mile Creek is due to the process of suction. The theory of suction removing large blocks of rock has been studied from the aspect of channel deepening in bedrock channels, but no research was found to mention the process of side suction, although it is believed to work in a similar way.

Experimental work was performed in a re-circulating flume to test the theory of removal of side blocks by suction. Experiments were performed to determine the hydraulic and geometric conditions for block removal. Pinpointing the conditions that caused block removal proved to be difficult due to the sporadic nature of suction removal. In order for suction to occur the velocity of the water flowing past the block must be high enough to create a pressure difference. Velocity fluctuations may deviate from the mean velocity for a specific amount of time and pulses of faster moving water within the profile may be significant enough to cause the block to be removed by suction.

Flow velocities were studied for Forty Mile Creek by using field data collected during periods of extensive rainfall and snow melt. Flow data was calculated from the

hydraulic program HEC-RAS and was also received from Philips Engineering for a floodplain study they completed. Although all three sources of flow data were taken from the same general area of Forty Mile Creek the velocity data varied. Flow data computed by hydraulic programs are average velocities whereas surface velocities measured during fieldwork provided flow data for a specific location along the armourstone wall and therefore are higher. Stream restoration projects are typically based on hydraulic data computed by hydraulic programs.

1.4 Concluding Remarks

The design of bank stabilization structures is usually based on average velocities calculated by using hydraulic computer programs, but flow data collected during field work at Forty Mile Creek shows that velocities close to the wall can be higher than those computed by the programs. The experimental work showed that side wall blocks can be removed by suction and that short pulses of faster flowing water within the profile do occur, which could be a contributing cause towards armourstone failure. Physical and hydraulic evidence indicates that suction can cause blocks to be removed from the wall and therefore should be taken into design considerations.

Chapter 2 – Literature Review

This chapter will provide background information on vertical bank protection structures used in urban stream restoration. It will also discuss the existence of velocity fluctuations within the flow and provide examples relating high flow velocities to movement within the channel. The forces that contribute to the process of quarrying along bedrock channels will be outlined at the end of the chapter.

2.1 Streams and Urbanization

It is known that urbanization affects the discharge and the physical nature of a given stream by increasing the amount of impermeable surfaces within the drainage basin. Impermeable surfaces reduce the rate and the amount of rainfall infiltration into the soil which causes a reduction in the storage of precipitation and increases overland flow (Hollis, 1975). As the amount of runoff increases it causes streams to have an increase in flood peaks within a shorter lag time (Leopold, 1968). Urbanization also causes the sediment load to decrease within the watershed (Wolman, 1967). The amount of impermeable surfaces gradually increases as urban environments expand. The impermeable surface area of the continental United States (48 states and Washington D.C.) is approximately 112, 610 km^2, with a standard deviation of +/- 12,725 km^2, which is slightly smaller than the total area of the state of Ohio (Elvidge *et al.*, 2004). The majority of these impervious surfaces are concentrated on the eastern half of the country (Elvidge *et al.*, 2004). A similar situation may be occurring in Southern Ontario where a large amount of impermeable surfaces are present in urban areas. Research suggests that streams within smaller and more permeable watersheds show signs of a greater and more immediate erosive response to urbanization (Bledsoe and Watson, 2001) and that smaller, more frequent floods are significantly increased by urbanization (Hollis, 1975). This instability of the stream dictates the need for adequate bank stabilization structures which are designed for a specific return period event in order to prevent significant erosion of the surrounding land.

2.2 Restoration Techniques

Essentially, there are three categories of bank stabilization practices which are: bioengineering, where vegetation is used to stabilize the bank; biotechnical, which is a combination of vegetation and structural; and lastly structural engineering. Each type of restoration structure has its own advantages and disadvantages which determine its suitability for a certain stream.

Bioengineering provides ecological benefits for habitat, it is appealing to look at and it can provide structural support for some streambanks. Bioengineering can vary from simply planting vegetation along the bank or it can be a more elaborate structure such as a crib wall. Biotechnical combines the use of vegetation with revetments so that both provide structural support for the streambank. Types of biotechnical techniques include vegetated rock walls and gabion baskets. Descriptions of bioengineering and biotechnical will not be mentioned because they are beyond the scope of this study. Structural solutions typically are hard rigid structures, which force the stream to remain in a static position and prevent the flowing water from eroding the bank material. The most common types of structural bank protection include: concrete; gabion baskets; riprap; and armourstone. Descriptions for these four structures are mentioned below providing background information on vertical and near vertical bank protection structures.

2.2.1 Concrete

Concrete can be used for bank stabilization because it can conform to any shape and angle of the bank and it has a high resistance to excessive flow velocities (American Society of Civil Engineers, 1992). The problems with using concrete include high maintenance expenses over time due to cracking and settlement (Figure 2.1) (American Society of Civil Engineers, 1992), as well as the effects of high discharges that cause overflow, allowing water to pass behind the structure possibly forcing the wall to be pushed forward (Fujita and Muramoto, 1995). Another problem with the use of concrete in the stream is that it causes a serious negative impact on the ecological nature of the

stream, especially if the entire channel is lined with concrete. This is due to the fact that it inhibits the growth of vegetation which ultimately impacts the habitat within the stream.

2.2.2 Gabion Baskets

Gabion baskets can be found in most restoration works and basically consist of galvanized wire cages that can be stacked on top of each other and are typically filled with small stone (Figure 2.2). It is stressed that the expected amount of scour should be calculated for the specific project so that undermining of the structure does not occur (Freeman and Fischenich, 2000). If the structure is damaged due to scour then it will either cause the basket to lose the stones held within it or the basket could slump forward, though this could be favorable because it could delay further scour from occurring.

It is stated by the Maryland Department of the Environment Water Management Administration (2000) that "gabion revetments should be used cautiously in high velocity streams", this could possibly be due to damage caused by debris or bedload material, or even to the risk of the cage deforming. Large material that comes in contact with the wire could cause it to be damaged which would lead to failure. The stone size chosen to fill the baskets depends on the size of the basket and the recommended shape of the stone should be angular and blocky (American Society of Civil Engineers, 1992). Problems can occur to the basket if the stones within it are not adequately sized to resist the forces of the flow (Freeman and Fischenich, 2000).

2.2.3 Riprap

Riprap is a very common stabilization technique and the design basically consists of various sized stones placed along a channel bank to protect it from the erosive forces of flowing water (Figure 2.3) (Maryland Department of the Environment Water Management Administration, 2000). The steepness of the bank determines the stability of the riprap and it is recommended that the slope not exceed 2H:1V (Biedenharn *et al.*, 1997a).

Figure 2.1 A concrete wall along Forty Mile Creek in Grimsby, Ontario. A large crack running down the wall can be noticed, which is also forcing the gabion basket on top of the wall to be pulled apart.

Figure 2.2 Gabion baskets lining a section of the bank along Loyalist Creek, Mississauga, Ontario. Photo is looking upstream. On the left hand side of the photo the gabion baskets are lining the bank adjacent to a public trail; on the right hand side the gabion baskets are protecting residential property.

The two most important characteristics for the hydraulic properties of riprap are the gradation and stone shape of the rock used. Usually the mixture is well graded, with the size and weight of the stone being the controlling limits of the sample (Biedenharn *et al.*, 1997a). The design flow velocity should be the basis for the maximum diameter or weight of the stone chosen (Maryland Department of the Environment Water Management Administration, 2000). It is believed that the 2 to 10 year return exerts the most energy against riprap and therefore is typically chosen as the design discharge (Fischenich, 2003). The stones used in riprap protection should be field or quarry stone; have a specific gravity of at least 2.5; and should be somewhat angular and blocky (American Society of Civil Engineers, 1992). The shapes of the rocks used in riprap protection are based on their long axis/short axis ratio. It is suggested that a maximum of 30% of the stones should have a long axis/short axis ratio greater than 2.5; a maximum of 15% should have a long axis/short axis ratio greater than 3.0; and none of the stones should have a long axis/short axis ratio greater than 3.5 (Biedenharn *et al.* 1997a).

2.2.4 Armourstone

Armourstone revetments consist of large, rectangular blocks of stone that are placed on top of each other forming a wall along the streambank (Figure 2.4). A typical long axis length for the stone used is around 100cm and the length of the short axis is usually below 70cm. It is these large stones that make up the main structural component of the wall. It is believed that the size/weight of the stones within the wall is more than adequate to prevent any damage from flowing water as long as the size is based on the design storm event and that the length of the longest axis is greater than 1/3 the height of the wall (Maryland Department of the Environment Water Management Administration, 2000). It is recommended that each of the rocks have a shape that is angular and blocky so that they are stackable (Maryland Department of the Environment Water Management Administration, 2000).

Benefits mentioned for this type of structure include its suitability to prevent severe erosion; stabilizing banks that have already experienced failure; and it can be used along steep and vertical banks (Great Britain Environment Agency, 1999). The toe area

Figure 2.3 Riprap lining a section of the bank along Loyalist Creek, Mississauga, Ontario. Photo is looking downstream. This picture was taken shortly after installation, February 2004.

Figure 2.4 Armourstone wall lining a section of the bank along Forty Mile Creek, Grimsby, Ontario. Photo is looking downstream. The armourstone wall is protecting adjacent parkland from erosion.

of the bank can be protected using a number of different approaches. The first way is to place the bottom row of stones below the stream bed to the expected scour depth (Escarameia, 1998). The second way is to just place the bottom layer of stone directly on top of the stream bed, though future problems can be expected because toe scour will eventually remove the base support for the wall. The third possibility is to build a toe trench in front of the bottom row of stones, which is filled with riprap (Maryland Department of the Environment Water Management Administration, 2000).

2.3 Engineering Design

Determining which bank stabilization structure should be used depends on the hydraulic conditions of the stream. Flow velocity and shear stress are the two main criteria that can lead to erosion problems because both influence the forces causing resistance and movement. Discharges and durations studied from design hydrographs also influence the design of bank stabilization (American Society of Civil Engineers, 1992). It is common to use shear stress and velocity associated with a recurring flow event to determine the size of stone and the design of many types of stabilization structures (Biedenharn *et al.*, 1997b). The problem with velocity and shear stress is that they are not steady or uniform in natural channels (Fischenich, 2001). Mean velocities are used to determine which structure would best protect against erosion, but the shape and depth of the channel must be taken into consideration because they can influence the forces acting on their boundaries (Fischenich, 2001). There are also short term pulses within the flow that can that can be 2 to 3 times higher than the average velocity, giving misleading results for erosion potential (Fischenich, 2001).

The relationship between discharge, hydraulic gradient, channel geometry, and roughness coefficient is typically done using computer modeling programs such as HEC RAS (Fischenich, 2001). These programs are referred to as the standard step-backwater method, which use the energy equation to compute the water stage within the channel (Miller and Cluer, 1998; Webb and Jarrett, 2002). HEC RAS can be used to determine hydraulic calculations for steady, gradually varied, one-dimensional, open channel flows (Copeland *et al.*, 2001). Channel cross sections, slopes, and Manning's coefficients are

determined from fieldwork and the program computes the main channel velocity and shear stress for each of the cross sections (Fischenich, 2001). These types of programs provide average velocities and do not illustrate the significance of fluctuations within the flow.

2.4 Near Critical Flow and Turbulent Flow Structures

2.4.1 Near Critical Flow

Flows within a channel are classified as subcritical, critical, or supercritical depending on the discharge and energy within a given cross section. When the flow is critical ($Fr \approx 1$) the stream is at its maximum efficiency.

The occurrence of critical flow along the thalweg within a stream can be calculated by solving for critical slope, which determines the slope needed for critical flow to exist (Tinkler, 1997). The equation is:

$$s_{crit} = gn^2d^{-0.33} \qquad \textbf{Equation 2.1}$$

where s_{crit} is the critical slope; g is the force due to gravity; n is the Mannings number; and d is depth.

Solving for critical slope in Forty Mile Creek, Grimsby:

$$s_{crit} = (9.81)(0.04^2)(2.0^{-0.33})$$
$$s_{crit} = 0.0125$$

The critical slope is similar to the field measured slope, which is approximately 0.016 for the study reach at Forty Mile Creek, indicating the possibility of occurrence of critical flow. Critical flow has been identified in Forty Mile Creek during fieldwork for this paper and Tinkler and Parish (1998) have identified critical flow along Cooksville Creek in Mississauga, Ontario.

2.4.2 Turbulent Flow Structures

Research has shown that velocity within a channel varies with time and spatiality. Large scale flow structures have been identified by researchers in gravel bed streams, as well as in experimental work on smooth beds, which have similar scaling even though the bed material differ (Roy *et al.*, 2004). These flow structures are described as wedges of high and low velocities occupying the entire flow depth and have a shape that is narrow and elongated (Roy *et al.*, 2004). These fluctuations of velocity are defined as "deviations of the instantaneous velocity from the time series average velocity" (Buffin-Belanger *et al.*, 2000). The large scale flow structures have a moderately low frequency of occurrence (mean of 9 events per minute) and a long duration (more than 2 seconds) from the research of Buffin-Belanger *et al.*, (2000). The interaction between flow structures in turbulent flow creates fluctuations in velocity for the downstream, vertical, and lateral flows (Roy *et al.*, 1999), which makes it difficult to make specific statements about velocities at any one point, which highlights the problem when design of bank protection structures is based on velocity.

2.5 Removal of Blocks Due to Suction

2.5.1 Velocities and Movement

The possibility of velocities significantly fluctuating from the mean can mislead the engineer about the stability of a bank stabilization structure. The effects of flood flows on concrete revetments was studied by Fujita and Muramoto (1995), where the combination of overtopping and high channel velocities left the revetment vulnerable to lift and drag forces. Failure occurred by both toppling and the complete removal of the concrete wall in pieces. Sumer et al, (2001) studied the removal of sediment from between armour blocks along the streambed through experimental work. They concluded that increased flow velocities can cause vortices to form in holes between the blocks, as the vortex dissipates into the main flow it entrains the sediment particle. The ratio of agitating forces (vertical pressure gradient, drag force, other forces) that suck the particle out, to the resistance (largely submerged weight of the particle) is how they define the critical condition for sediment removal. The force of flowing water has the ability to

move large boulders along the bed and the stability of large boulders was studied by Graf (1979), where stability depended on the ratio of force (of flowing water) to resistance, with the main components consisting of the buoyant weight of the boulder, friction, and velocity. The force caused by high flow velocities within a bedrock channel can also lead to large blocks of stone being lifted from the bed due to suction. This process is known as quarrying or hydraulic plucking and flow velocities are an essential factor contributing to it. The following sections will focus on the components required to lift the blocks off the bed in order to apply them to the process of lateral suction discussed in chapter 4.

2.5.2 Quarrying

Pressure differences that occur between the flowing water traveling overtop of the block and the stationary water that is within the joints can be significant enough to lift the block off the bed (see Figure 2.5); (Reinius, 1986). According to Reinius (1986) resistance to lift depends on shape, weight, and shear forces between adjoining blocks and that interlocking of the block lessens the risk of erosion. The area in which the pressure is acting on will be subjected to uplift forces (Reinius, 1986). The forces that keep the block in place are: the buoyant weight of the block, friction on the upstream and downstream edges of the block, as well as instantaneous pressure forces along the top surface area of the block (Whipple *et al.*, 2000). The forces that could cause lift are instantaneous pressure forces along the bottom surface area of the block, and possibly drag forces on exposed vertical edges (Whipple *et al.*, 2000); (see Figure 2.5).

The Bernoulli principle is used to describe the initial cause of suction for large blocks off the bed. The theory behind it is that the higher the velocity of a fluid is, the lower the pressure will be. The top of the block will be impacted by the fast flowing stream flow, whereas the water within the joints is almost stationary. This pressure differential, as well as other hydraulic and physical variables contributes to suction removing large blocks of stone off the bed. Both Hancock *et al.* (1998) and Wende (1999) used formulas to represent the forces of movement and resistance for block removal due to quarrying.

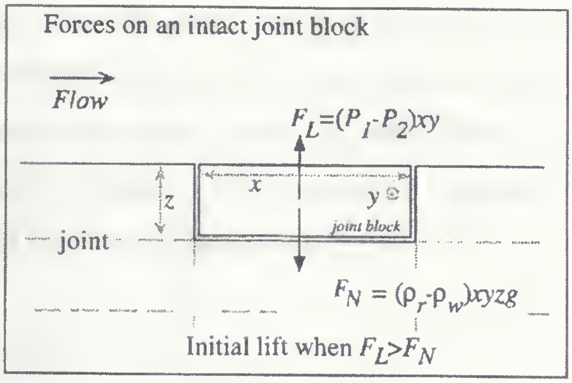

Figure 2.5 Diagram depicting the forces impacting a block along the stream bed causing quarrying to occur, where F_L represents the lift force and F_N represents the buoyant weight of the block. The length of the block that is of importance for quarrying to occur is the z direction, whereas for side suction it is the y direction. Altered from its original source (Hancock *et al.*, 1998).

2.5.3 Components of Quarrying

The two formulas used by Hancock *et al.* (1998) are the lift force (equation 2.2) and the buoyant weight of the block (equation 2.3). For the block to be removed the lift force has to be greater than the buoyant weight of the block (Hancock *et al.*, 1998).

$$F_L = (P_1 - P_2)xy \qquad \textbf{Equation 2.2}$$

$$F_N = g(\rho_r - \rho_w)xyz \qquad \textbf{Equation 2.3}$$

where P_1 and P_2 are the pressure exerted on the bottom and top of the rock respectively and are controlled by flow velocity; x is the length of the block that is parallel to the main flow, y is the length of the block that is horizontally perpendicular to x, and z is the vertical length of the block; ρ_r and ρ_w are the density of the bedrock and the water respectively; and g is the acceleration due to gravity.

Wende (1999) also studied quarrying in hard rock systems through the process of lifting forces overcoming the frictional and gravitational forces which cause the block to be removed by suction. The submerged weight and the friction force (equation 2.4) are stated as the principle forces resisting movement; the drag (equation 2.5) and lift (equation 2.6) are stated as the driving forces (Wende, 1999). The formula for submerged weight used by Wende (1999) is essentially the same as the buoyant weight formula (equation 2.3) used by Hancock *et al.* (1998).

The friction force formula is:

$$F_F = \mu_f F_R \qquad \textbf{Equation 2.4}$$

where F_R is the resultant force of F_N and F_L acting normal to the surface, and μ_f is the coefficient of friction where the value depends on the amount of interlocking, making this value difficult to predict accurately.

Forces that are impacting the block and that are caused by the flow are the drag and lift forces. The drag force would only be taken into consideration if the block was protruding from the bed. The formula representing the drag force is:

$$F_D = (1/2)(C_D A_f \rho_w V^2) \qquad \textbf{Equation 2.5}$$

where C_D is the drag coefficient which depends on the shape and orientation of the block; A_f is the area perpendicular to the flow; ρ_w is the fluid density; and V is the flow velocity. The lift force is the result of the pressure differences along the top of the block and below it (Wende, 1999). The formula representing the lift force is:

$$F_L = (1/2)(C_L A_p \rho_w V^2) \qquad \textbf{Equation 2.6}$$

where C_L is the lift coefficient, which depends on various parameters; A_p is the area parallel to the flow.

2.5.4 Threshold Velocity

Both Hancock *et al.* (1998) and Wende (1999) provided similar formulas to determine the threshold velocity for quarrying to occur. In both equations the thickness of the block (z) is the only direction that affects lift. The equation used by Hancock *et al.* (1998) to estimate the threshold velocity to initiate lift is:

$$v_t = [\ (2gz/\rho_w)\ (\rho_r - \rho_w)]^{\frac{1}{2}} \qquad \textbf{Equation 2.7}$$

where v_t is the threshold velocity required to initiate lift of the block; g is the acceleration due to gravity; z is the thickness of the block; ρ_w is the density of water; and ρ_r is the density of the bedrock. Threshold velocities can be calculated to determine the approximate velocities needed to cause movement of the block away from the bed.

2.6 Concluding Remarks

Urbanization has required the need for bank protection structures and the design of these structures are primarily based on mean flow velocities, which do not take into consideration flow fluctuations which can be significantly higher. The main variables that contribute to quarrying are: the shape of the block, the buoyant weight of the block, friction, and flow velocities. The possibility of these forces affecting the armourstone wall, leading to block removal by lateral suction will be further illustrated in the following chapters.

Chapter 3 – Review and Field Assessment of Standards for Armourstone

This chapter will provide general information regarding the design and the modes of failure for armourstone revetments. The general physical setting for each of the armourstone walls studied during fieldwork will be provided, with a specific focus on the wall at Forty Mile Creek in Grimsby, Ontario.

3.1 Armourstone Revetment Design Standards

When a structure is built for streambank protection there are typically guidelines to follow, such as how to prepare the stream and the bank for construction, as well as how to build the structure. Normally it is not too difficult to find adequate design standards for a specific structure but it proved to be more complicated finding some for armourstone revetments. Design standards were provided in guidelines put together by Maryland Department of the Environment Water Management Administration (here on referred to Maryland's Guidelines, 2000) for imbricated riprap (equivalent to armourstone) where the standards that should be considered when building are mentioned. The Maryland Guidelines (2000) state that armourstone revetments are ideal for streams where the possibility of erosion occurring under the design flow conditions exist, such as poor soil conditions or high velocities and turbulence. Because this guideline contained the most detail, it was used as a comparison for fieldwork locations in Mississauga, Burlington, and Grimsby Ontario. The lack of specific design standards lead to studying armourstone walls more closely in the field in order to identify how these walls are built and common modes of failure.

3.2 Types of Armourstone Failure

Some degree of structural failure was noticed in almost all of the creeks that were studied, with the most common being the removal of stones from the wall. Two explanations for block removal are due to noticeable scour at the toe and overflow which can push the stone out. Since there was no apparent toe scour and substantial

overtopping is not known to have occurred at Forty Mile Creek, there must be another mode of failure.

Three possibilities causing failure are:

1. The loss of base support due to toe scour (see Figures 3.1 and 3.2). The most obvious examples of this type of failure can be found along Cooksville Creek in Mississauga where the bed of the creek consists of weak shale that is easily eroded (Tinkler and Parish, 1998). When the shale is kept wet it is actually very strong, but when this shale dries it becomes very weak and is susceptible to erosion. Large gaps beneath armourstones where the shale has been eroded are easy to identify. Failure occurs because the stone loses its base support and then begins to slump forward; ultimately causing the upper stones to slump forward as well.
2. Failure can also occur by substantial overtopping of water caused by bank overflow. If a significant amount of water is able to get behind the stone it may be able to push the block out.
3. The main focus of this research is defined by the next possible mode of failure. Water surrounding the armourstone would lead to a pressure difference between the streamside and backside of the stone, therefore causing suction to occur. This seems to be the mode of failure for the reach of Forty Mile Creek in Coronation Park, Grimsby where two stones were removed from the wall (Figure 3.3). This process seems to occur in a manner that is similar to quarrying blocks of rock off the streambed. The process of side suction will be explained in detail in the next chapter.

Figure 3.1 Cooksville Creek, Mississauga, Ontario. The streambed is composed of weak shale and it can be seen that underneath the armourstones that the shale has been eroded and large gaps are present

Figure 3.2 Cooksville Creek, Mississauga, Ontario. This picture shows the collapse of the armourstone wall due to the removal of the shale which supports the armourstone. Photo was taken in 1997.

Figure 3.3 Forty Mile Creek, Grimsby, Ontario. Two armourstones were removed from the wall and it can be seen that the base stone is still in tact and undermining has not occurred.

3.3 General Physical Setting – Fieldwork Sites in Southern Ontario

3.3.1 Armourstone Walls at Field Sites

Seven armourstone walls were chosen along five streams to study the similarities between them. Below is a general description of each of the walls and their locations, specific details on the design of these walls are discussed in chapters 5 and 6.

1. Forty Mile Creek in Grimsby, Ontario. This wall is located in Coronation Park just below the Niagara Escarpment. The armourstone wall underwent restoration work in October of 2003 and it is the restored wall that is used in the fieldwork comparison. The approximate length of the wall is 55m (Figure 3.4).
2. Tuck Creek in Burlington, Ontario; this wall is located in between Spruce Street and Lakeshore Road. The estimated length of the wall is 65m (Figure 3.5).
3. Appleby Creek in Burlington, Ontario; this wall is located at Spruce Street. The approximate length of the wall is 19.5m (Figure 3.6).
4. Cooksville Creek in Mississauga, Ontario; the first location is near Robert Speck Parkway. Approximate length of the wall is 440m (Figure 3.7).
5. Cooksville Creek in Mississauga, Ontario; the second location is near Mississauga Valley Boulevard. Approximate length of the wall is 145m (Figure 3.8).
6. Cooksville Creek in Mississauga, Ontario; the third location is near Aqua Drive. Approximate length of the wall is 1,120m (Figure 3.9).
7. Loyalist Creek in Mississauga, Ontario; this wall is located at Thorn Lodge Drive. Approximate length of the wall is 330m (Figure 3.10).

3.3.2 Geology

Each of the creeks within the field study has stream beds that consist of weak shale (see Figure 3.11 for overview of locations). In Grimsby and Burlington the shale is Queenston Formation (Ordovician) and in Mississauga the shale is Georgian Bay Formation (Ordovician); (Chapman and Putnam, 1984). The Queenston Formation is mostly red shale with thin interbeds of calcareous sandstone, siltstone, and fossiliferous siltstone to limestone; the Georgian Bay Formation is grey shale with bioclastic-rich

Figure 3.4 Armourstone wall along Forty Mile Creek in Grimsby, Ontario. The right side of the photo is Coronation Park. Photo is looking upstream.

Figure 3.5 Armourstone wall along Tuck Creek Burlington, Ontario. The right side of the photo is residential property. Photo is looking downstream.

Figure 3.6 Armourstone wall along Appleby Creek Burlington, Ontario. The wall is protecting residential property. The creek flows from right to left.

Figure 3.7 Armourstone wall along Cooksville Creek near Robert Speck Parkway, Mississauga, Ontario. Armourstone walls are on both sides of the creek and this wall is located within an urban area.

Figure 3.8 Stepped armourstone wall and stepped weir along Cooksville Creek near Mississauga Valley Boulevard, Mississauga, Ontario. Photo is looking upstream.

Figure 3.9 Armourstone wall along Cooksville Creek near Aqua Drive, Mississauga, Ontario. Photo is looking downstream. Photo shows the transition from 4 stones to 3 (indicated by white arrows) and also shows the shale bed undercutting the stones (indicated by black arrow).

Figure 3.10 Armourstone wall along Loyalist Creek, Mississauga, Ontario. Upstream is to the right of the photo.

limestone beds (Brogly *et al.*, 1998). The Georgian Bay Formation is thicker at about 180m and the Queenston Formation 130m thick (Russell, 1981).

Tuck and Appleby creeks both flow in a south-easterly direction towards Lake Ontario. The approximate watershed size is 34 km^2 for Tuck Creek and 10 km^2 for Appleby Creek. The land use within the watersheds is high density housing (Figures 3.12 and 3.13).

Cooksville Creek flows in a south-easterly direction and Loyalist Creek flows in an easterly direction. Cooksville Creek flows into Lake Ontario and the size of the watershed is about 30 km^2 (Figures 3.14, 3.15, and 3.16). Loyalist Creek flows into the Credit River and the size of the watershed is approximately 13km^2. The land use within these watersheds is also high density housing (Figure 3.17).

3.4 Forty Mile Creek, Grimsby

3.4.1 Physical Setting

More detail is mentioned for Forty Mile Creek due to the fact that this armourstone wall is the main focus of this paper. Forty Mile Creek in Grimsby, Ontario runs from the top of the escarpment to Lake Ontario with a drainage basin approximately 37km^2. Urbanization on the top of escarpment is limited to a small number of houses and consists mostly of agriculture. Below the escarpment the creek runs through the downtown core of Grimsby and is therefore surrounded by urbanization. The creek drops down approximately 90m from the top of the escarpment where it flows through Coronation Park at the base of the escarpment. The length of the creek through this park is approximately 250m, with a slope of approximately 0.016. The stream bed within this area consists mostly of gravel and small stones which overlays a bed of Queenston Shale. A map of Grimsby from 1876 shows that Forty Mile Creek actually braided within this section (Figure 3.18) and this would have been caused by the presence of gravel within the stream. Now, this creek is a single channel and a variety of bank protection works can be found on both sides of this section of Forty Mile Creek (Figure 3.19). During

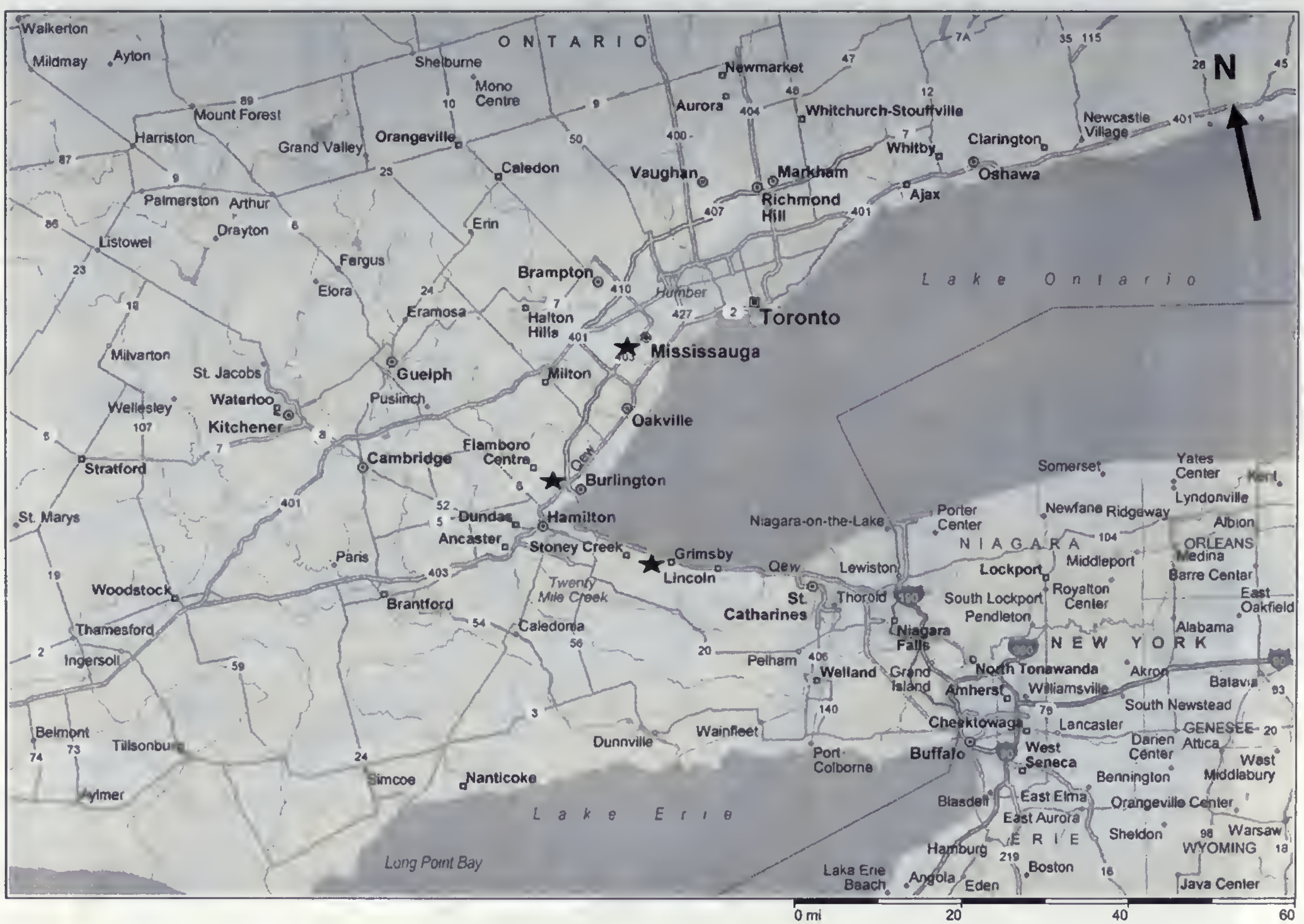

Figure 3.11 Overview of locations of Grimsby, Burlington, and Mississauga, Ontario (indicated with stars) where armourstone walls are located. Map altered from original source (Microsoft. Streets and Trips 2005. [Electronic Resource]. Microsoft Corporation, Redmond, WA 2004).

Figure 3.12 Approximate location of armourstone wall (represented by black circle) along Tuck Creek in Burlington, Ontario. Map was altered from its original source (Mapsource. TOPO Canada Version 2. [Electronic Resource]. ˙Garmin International Inc. Olathe, Kanas [2003]).

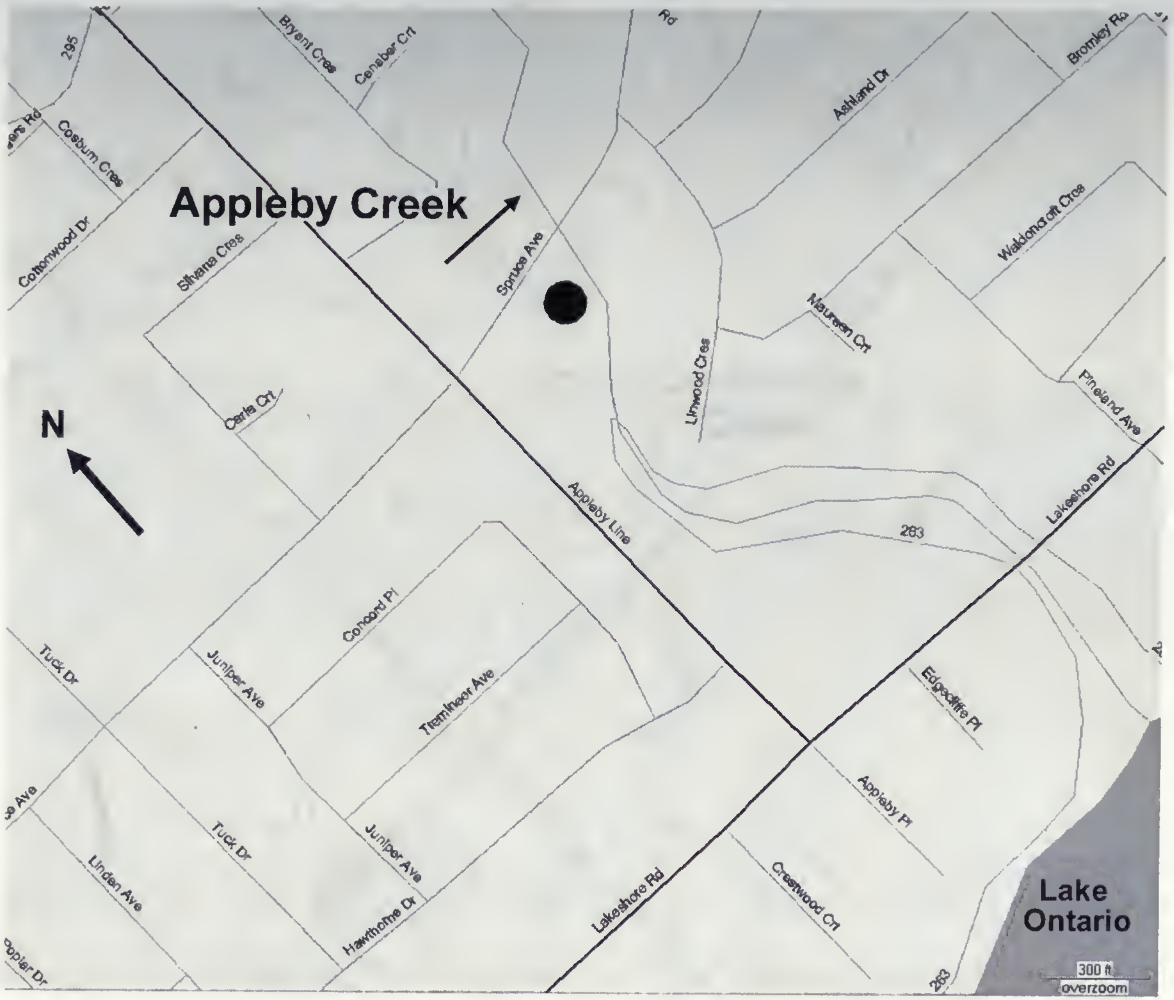

Figure 3.13 Approximate location of armourstone wall (represented by black circle) along Appleby Creek in Burlington, Ontario. Map was altered from its original source (MapSource. TOPO Canada Version 2. [Electronic Resource]. Garmin International Inc. Olathe, Kansas [2003]).

Figure 3.14 Approximate location of armourstone wall (represented by black circle) along Cooksville Creek near Robert Speck Parkway, Mississauga, Ontario. Map was altered from its original source (MapSource. TOPO Canada Version 2. [Electronic Resource]. Garmin International Inc. Olathe, Kansas [2003]).

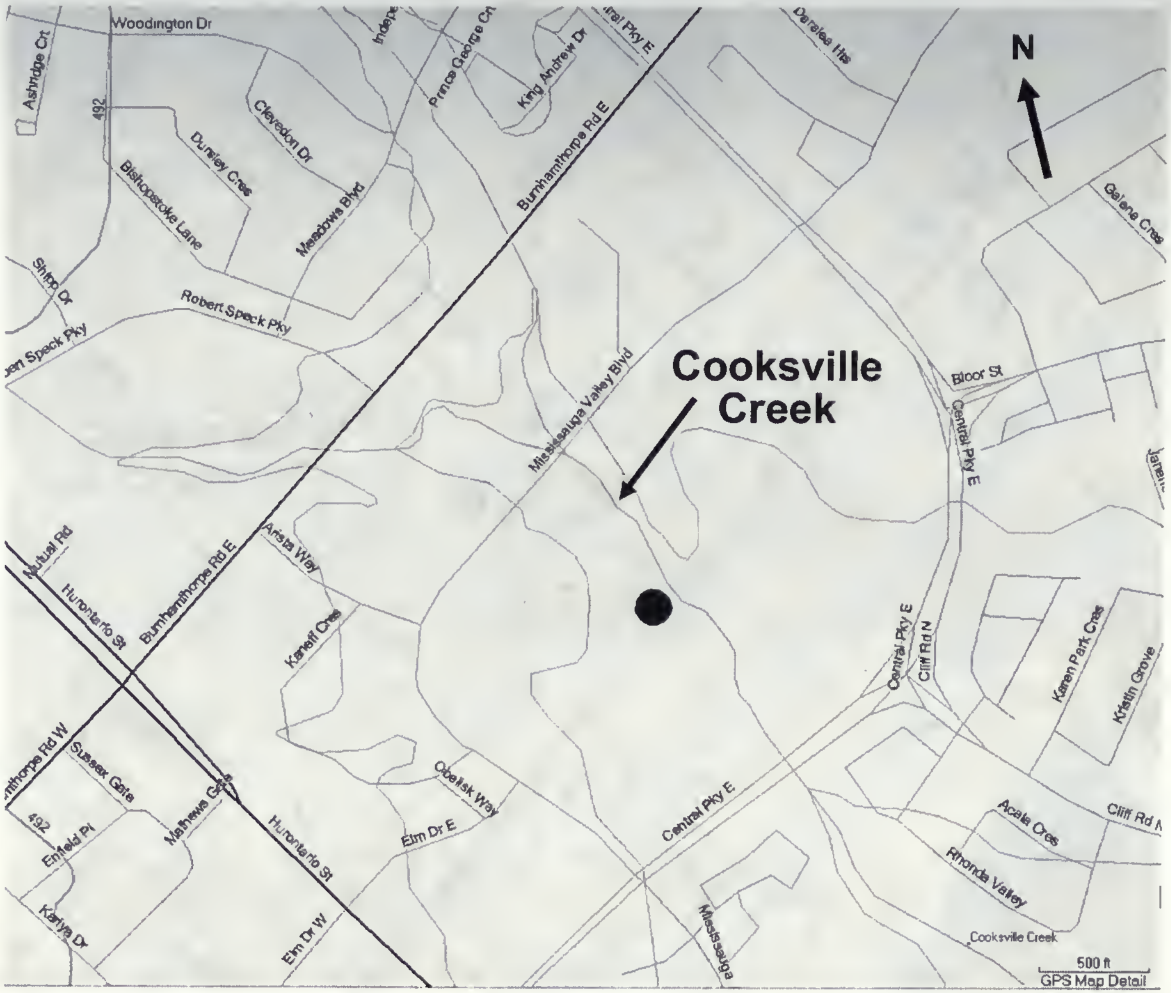

Figure 3.15 Approximate location of armourstone wall (represented by black circle) along Cooksville Creek near Mississauga Valley Boulevard, Mississauga, Ontario. Map was altered from its original source (MapSource. TOPO Canada Version 2. [Electronic Resource]. Garmin International Inc. Olathe, Kansas [2003]).

Figure 3.16 Approximate location of armourstone wall (represented by black circle) along Cooksville Creek near Aqua Drive, Mississauga, Ontario. Map was altered from its original source (MapSource. TOPO Canada Version 2.. [Electronic Resource]. Garmin International Inc. Olathe, Kansas [2003]).

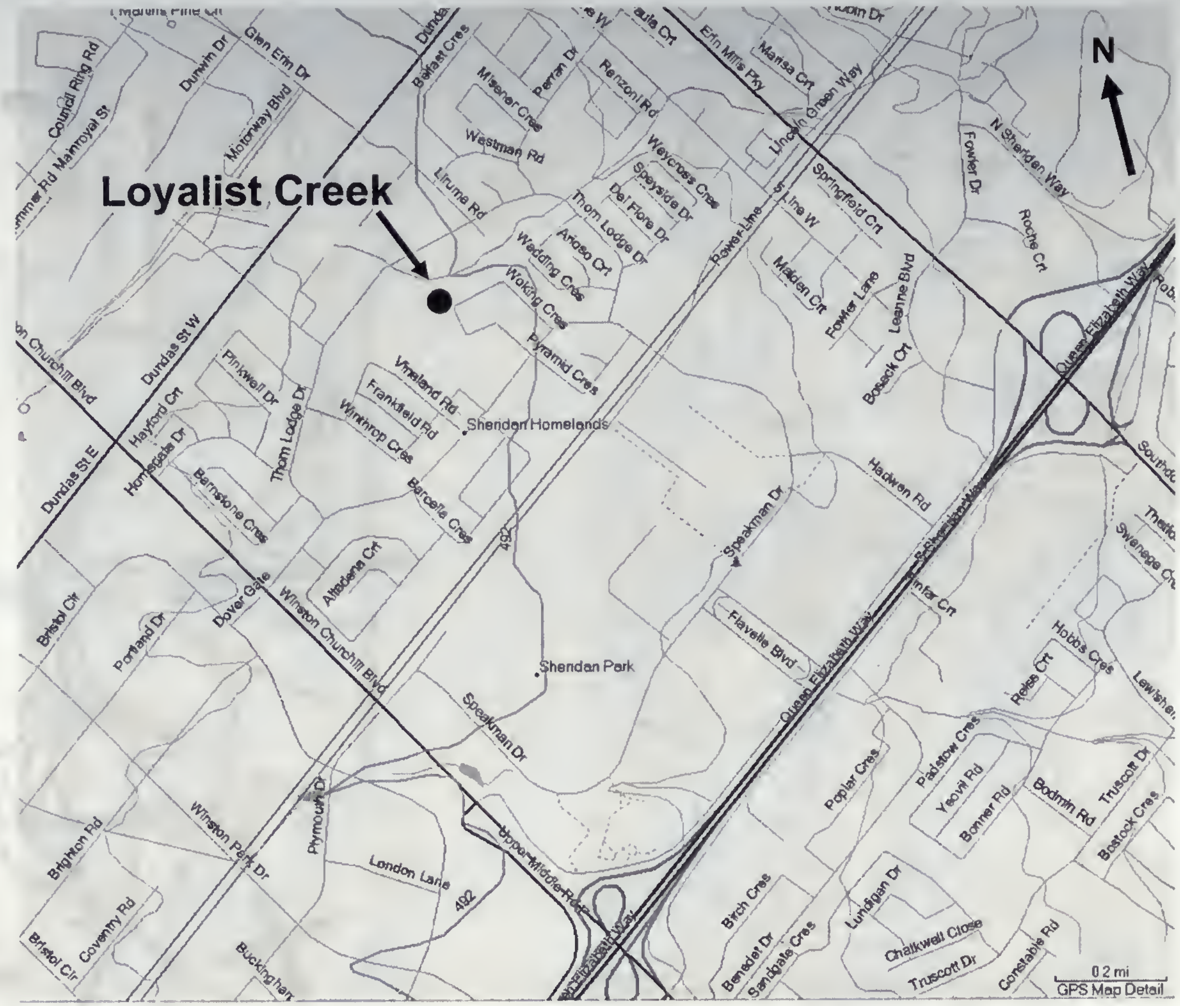

Figure 3.17 Approximate location of armourstone wall (represented by black circle) along Loyalist Creek near Thorn Lodge Drive, Mississauga, Ontario. Map was altered from original source (MapSource. TOPO Canada Version 2. [Electronic Resource]. Garmin International Inc. Olathe, Kansas [2003]).

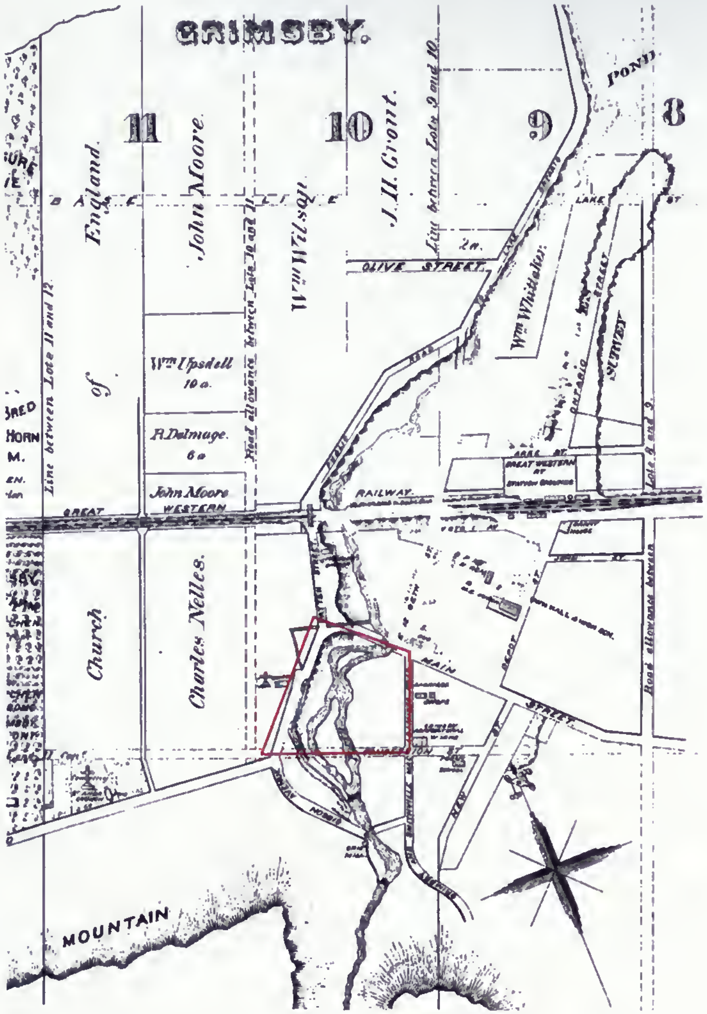

Figure 3.18 Map of Grimsby in 1876, study reach is outlined in red. Flow direction is from the bottom to the top of the map. Map is not to scale and has been altered from its original source (H.R. Page and Co., 1876).

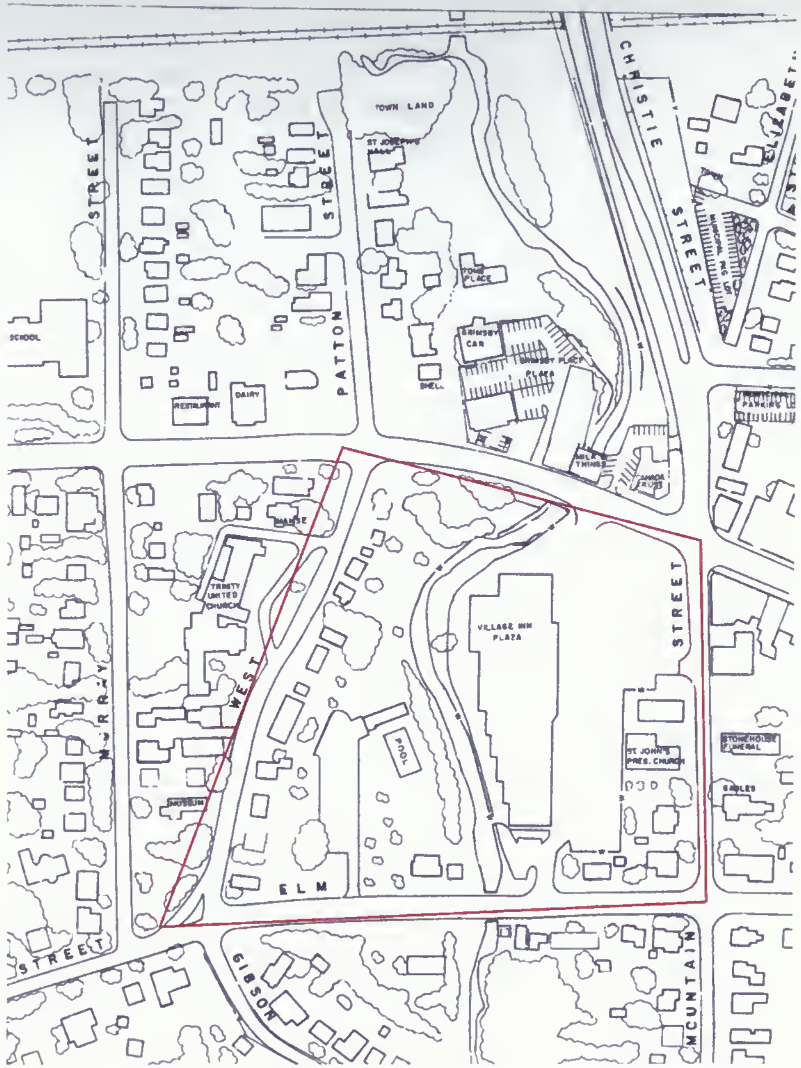

Figure 3.19 Recent map of the study reach for Forty Mile Creek. It can be seen that the stream no longer braids. Flow direction is from the bottom to the top of the map. Map is not to scale and has been altered from its original source (Grimsby (Ont.) Public Works Dept., 1999).

periods of high rainfall, and also in the spring when the snow begins to melt, relatively large discharges can be found in the creek. The section through Coronation Park receives high velocities which have required the need for bank protection structures within this area.

From the upstream end to downstream end of the reach, the left bank consists of approximately 135 m of natural bank, 55 m of armourstone, 44 m of concrete with gabion, and about 10 m of manmade/natural bank. The entire length of the right bank consists of gabion baskets (Figure 3.20). The armourstone wall within this area was built approximately in the mid 1980's to protect the bank along the outside of the stream bend. The armourstone consists of stones three high in the upstream end and then goes down to two high and finally down to one high before it reaches the concrete. On the opposite side of the stream bend a large bar has formed and contains vegetation and small trees. Within this area the stream bed deepens quite significantly creating a pool adjacent to the armourstone wall. Adjacent to where the two stones were removed the depth from the top of the bank to the streambed is 3.2 m for this section and at only 16 m upstream the depth is 2.1 m.

3.4.2 Failure at Forty Mile Creek

After a flood in the spring of 2003 (Figure 3.21) it was first noticed that two stones (in one column) had been removed from the wall and eventually it became apparent that the two stones lay directly in front of the wall on the bottom of the stream. The two stones rested on top of a base stone that was inset into the bed and this base stone was not removed. Due to the depth of this area it was difficult to assess whether the stones were removed due to toe scour because the depth of water even in the summer was still relatively deep. The surrounding stones though were still intact and did not seem to be impacted by scour because there was no significant leaning of the stones into the creek. What was apparent was the presence of large depressions in behind the stones on the downstream length of where the two stones came out (Figure 3.22). At high water stages during fieldwork water could be seen in between the stones and it is obvious that

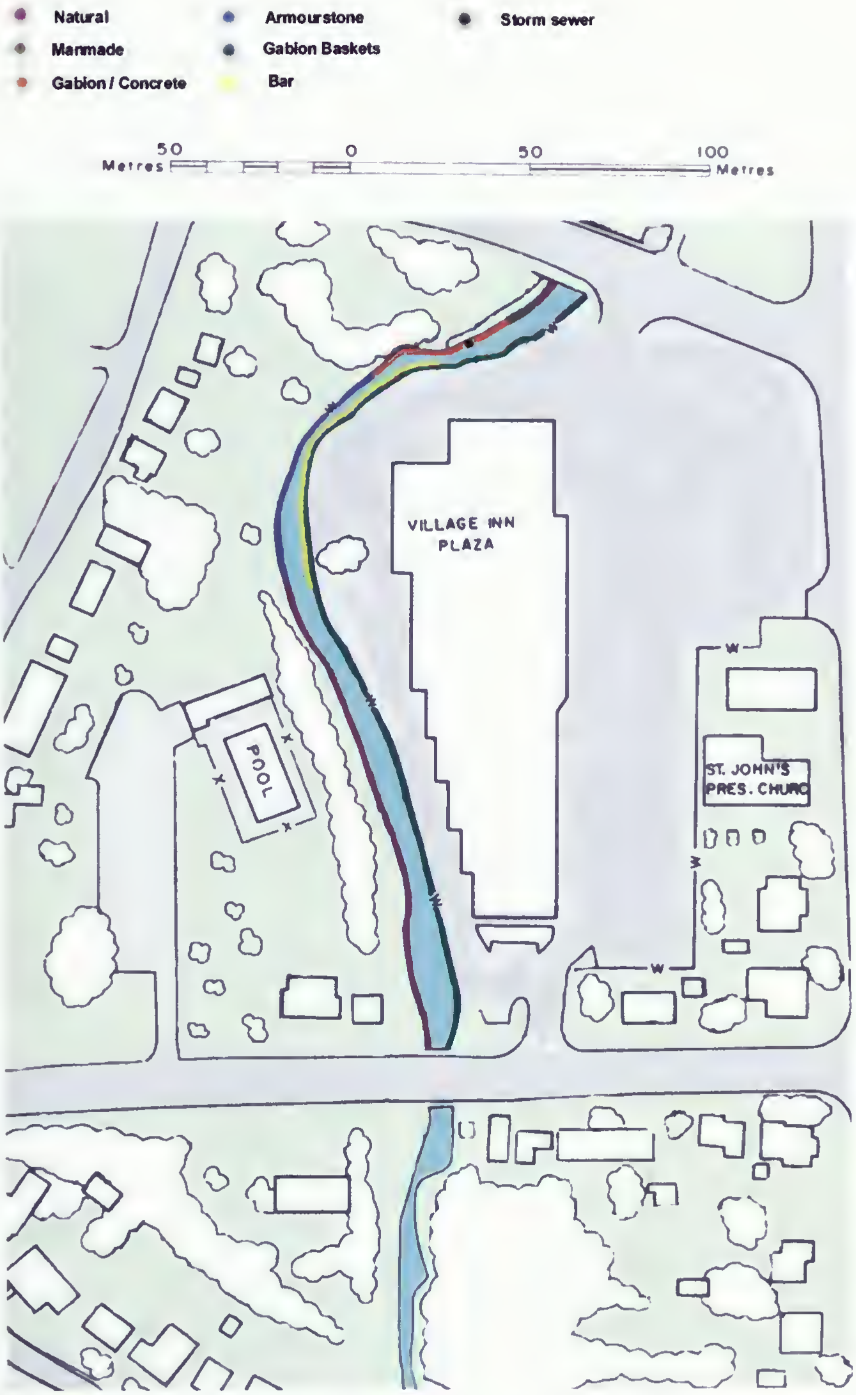

Figure 3.20 Map of study reach for Forty Mile Creek through Coronation Park in Grimsby, Ontario. Coloured lines represent the length and type of bank stabilization found on either side of the creek. Flow direction is from the bottom to the top of the map. Map has been altered from its original source (Grimsby (Ont.) Public Works Dept., 1999).

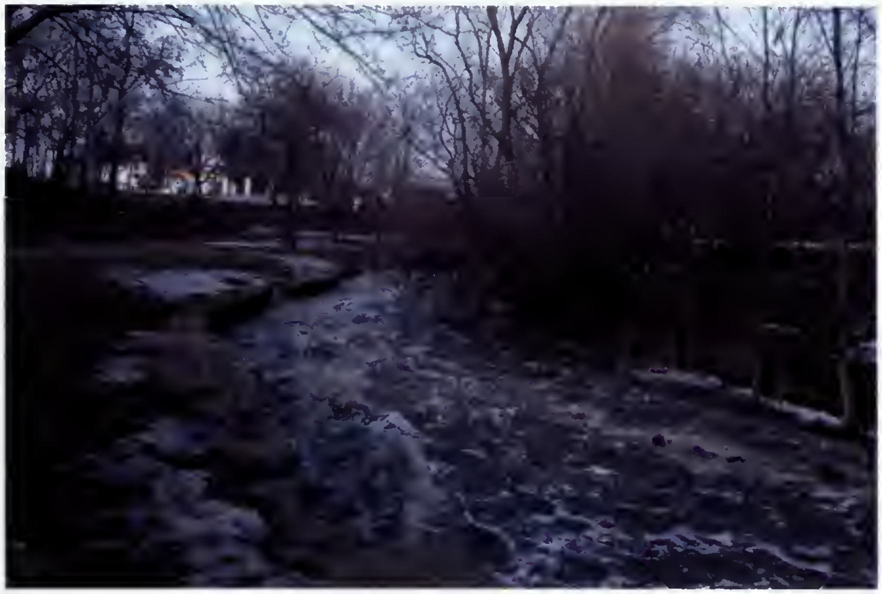

Figure 3.21 Forty Mile Creek, Grimsby, Ontario. This photo was taken in the spring of 2003, although no flow measurements were taken it can be seen that critical flow is occurring. The flow direction is from the bottom of the photo to the top.

Figure 3.22 Armourstone wall along Forty Mile Creek in Grimsby, Ontario before it was restored. Large depressions were noticed in behind the top layer of stones where sediment had been removed.

through time this caused the sediment to be removed from behind the wall creating these large depressions.

3.4.3 Restoration

In October 2003 restoration began on the armourstone wall within Coronation Park (see Figures 3.23 and 3.24). The project consisted of partial replacement of the armourstone wall, where the top two layers were removed and then they were replaced back on top of one another. All the same stones were used and about seven new stones were bought and placed within the structure. The stones were to be placed as close together as possible, again with their long axis running parallel to the stream. Riprap and geotextile material were placed in behind the wall similar to the design standard. The total cost of the restoration job was approximately $40,000. The gabion baskets on the opposite side of the stream as well as the concrete wall were not touched during this restoration job. Basically, it amounted to the removal of the upper stones and then the replacement of them. Because the base stones were not removed it would indicate that basal scour did not occur along the toe of the wall. Therefore one can assume that there was another force involved that removed these two stones from the wall, which will be further explored in the next chapter.

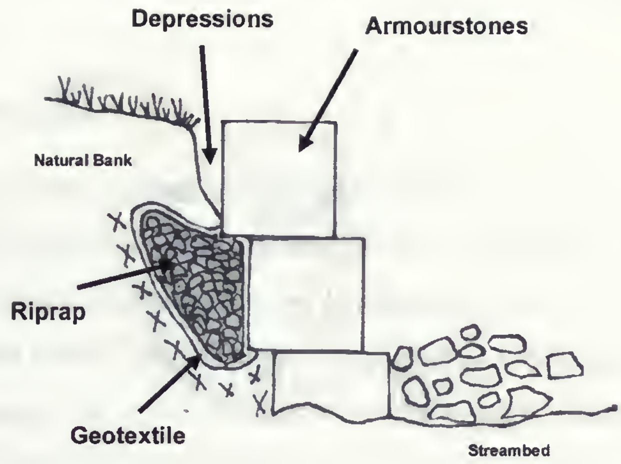

Figure 3.23 Diagram depicting the cross section of the original armourstone wall at Forty Mile Creek in Grimsby, Ontario. Depressions were observed in behind some of the top layer stones.

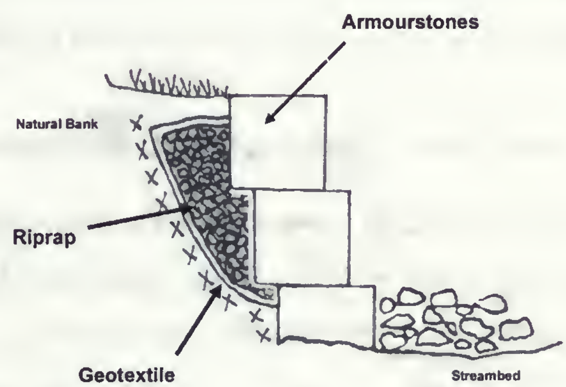

Figure 3.24 Diagram depicting the cross section of the restored armourstone wall at Forty Mile Creek in Grimsby, Ontario. A larger volume of riprap seems to have placed in behind the new armourstone wall.

Chapter 4 – Theoretical Criteria Controlling Suction

4.1 Block Stability

Hydraulic forces determine the stability of the armourstone block within the wall. In quarrying the stability of the block depends on the lift force and the buoyant weight of the block, which were determined by the formulas of Hancock et al. (1998) and Wende (1999) mentioned earlier. Similar circumstances exist for the armourstone block, where movement depends on the force exerted by the flow and the resistance of the block. Hancock et al. (1998) and Wende (1999) were concerned with the z direction for quarrying, when the block is in the wall the direction which is of concern for armourstone blocks is y. The only block dimension that is significant for suction to occur is the y direction, the x and z dimension do not affect whether suction will occur or not (Hancock et al., 1998; Wende, 1999) and the shape of the block only influences the resistance of the block (Reinius, 1986). The suction coefficient represents how well the suction force is coupled to the wall and in absence of experimental data is taken to be 1. The forces involved in the suctioning of armourstone blocks from the wall are discussed below.

4.1.2 Discussion of Forces Controlling the Stability of the Block

The velocity of the water within the channel is one of the significant factors for suction to occur, which relates back to the Bernoulli principle that was used by Hancock et al. (1998) and Wende (1999) for the quarrying process. The Bernoulli principle states that the higher the velocity of a fluid is, the lower the pressure will be (Equation 4.1). Water that is surrounding the block will have a relatively low velocity compared to the velocity of the water that is flowing through the channel. A pressure differential is created where the higher pressure is located behind the stone and the lower pressure is along the channel. As the velocity of the water increases, the flow force exerted also increases. The velocity value for the formula is also hard to determine accurately, due to the variability of flow. As was mentioned earlier and will be shown later in the experimental work, velocity is constantly fluctuating. The flow velocity can be

significantly above the mean velocity or it can be significantly below for any given amount of time.

The Bernoulli Equation is given as:

$$(P_a/\gamma)+V^2_a/2g) + a_a = (P_b/\gamma) + (V^2_b/2g) + a_b$$ **Equation 4.1**

$$(P_a-P_b)/\gamma = V_b^2/2g-V_a^2/2g$$

$$(P_a-P_b)/\gamma = (V_b^2-V_a^2)/2g$$

$$(P_a-P_b) = (\gamma/2g)(V_b^2-V_a^2)$$ (Robertson and Crowe, 1997)

where P is pressure, V is velocity, g is the gravitational constant, γ is specific weight of a fluid, and a is elevation at a specific point. The subscripts a and b represent different points in the flow field. It can be seen that this equation shows the inverse relationship of pressure to velocity.

The depth of water within the channel determines how much of the block is submerged with water, which influences the buoyant weight of the block. As the depth of water within the channel increases, the block resistance decreases. The buoyant weight of the block is one of the principle forces resisting motion (Wende, 1999).

Friction is also an important force causing the block to resist movement out of the wall. The friction value in the flume experiment (mentioned later) was determined experimentally, but determining friction for the armourstones is not as easily established. A friction value for armourstone blocks can be difficult to determine due to a number of reasons, most importantly are rough surfaces and the possibility of interlocking which can all lead to higher values of friction (Wende, 1999). The variability of the surface roughness for an armourstone block can lead to problems determining the exact friction value. Values for the angle of static friction can be taken from the angle of rest for boulders on hillsides or from experimentally determined ranges (Carling and Tinkler, 1998). The acceptable range of values for friction of large boulders seems to be between 0.70 and 0.90 for cases of sliding over hard surfaces (Carling and Tinkler, 1998; Wende,

1999). Ranges have been used due to the absence of useful alternatives and they can be explored in the spreadsheet.

The suction coefficient used in the formula is comparable to the lift coefficient in the formulas used for quarrying. It is used to explain the degree of coupling between the flow and the armourstone wall. The value 1 would indicate perfect coupling, which may not be the case, but it is used in the absence of experimental data. By changing this value in the spreadsheet one can assess the variability.

4.1.3 Example of Block Stability

A spreadsheet was developed to assist in manipulating the criteria controlling suction (see Appendix A). The spreadsheet allows hydraulic and physical variables to be entered: flow depth; flow velocity; rock dimensions; friction; and the suction coefficient (Tables 4.1, 4.2, and 4.3). Once these variables are entered suction and resistance can be calculated to determine whether suction of the block will occur.

Rock Properties	
Rock Dimension x	1.30m
Rock Dimension y	0.75m
Rock Dimension z	0.85m
Rock Density	2500kg/m^3
Friction	0.70

Table 4.1 Rock properties used in block stability examples.

Flow Properties	
Depth	0.75m
Water Density	1000kg/m^3
Suction Coefficient	1.00

Table 4.2 Flow properties used in block stability examples.

	Example 1	**Example 2**	**Example 3**
Flow Velocity	3.5m/sec	4.085m/sec	4.5m/sec

Table 4.3 Flow velocities used in block stability examples. The three velocities represent the velocities below, at, and above the value needed to remove the block away from the wall.

In order to determine the rock resistance in water the partial submerged mass must be determined.

$$PS_m = ((S_m)(d/z)) + ((z\text{-}d)/z)(\rho_r)$$ **Equation 4.2**

where PS_m is the partial submerged mass of the rock, S_m is the submerged mass, d is depth, z is the vertical length of the block, and ρ_r is the density of the rock.

Example 1, 2, and 3 $PS_m = ((1500kg/m^3)(0.75m/0.85m))+(0.85m-0.75m)/0.85)(2500kg/m^3)$
$= 1617.6kg/m^3$

Rock resistance is then solved:

$$R_R = (z)(x)(y)(PS_m)(g)(\mu_f)$$ **Equation 4.3**

where R_R is the rock resistance and μ_f is friction, y is the length of the block that is horizontally perpendicular to x, x is the length of the block that is parallel to the main flow, and g is the gravitational constant.

Example 1, 2, and 3 $R_R = (0.85m)(1.30m)(0.75m)(1617.6kg/m^3)(9.81m/s^2)(0.70)$
$= 9205.8$ Newtons

To solve for suction:

$$S = (z)(x)(\rho_w)(0.5)(V^2)(\mu_s)$$ **Equation 4.4**

where S is suction, ρ_w is the density of water, V is velocity, and μ_s is the suction coefficient. Three examples are used to represent the velocity below, at, and above the threshold velocity needed to remove the block from the wall.

Example 1 $S = (0.85m)(1.30m)(1000kg/m^3)(0.5)(3.5^2m/sec)(1.00)$
$= 6768.1$ Newtons

Example 2 $S = (0.85m)(1.30m)(1000kg/m^3)(0.5)(4.085^2m/sec)(1.00)$
$= 9219.7$ Newtons

Example 3 $S = (0.85m)(1.30m)(1000kg/m^3)(0.5)(4.5^2m/sec)(1.00)$
$= 11188.1$ Newtons

The ratio of suction to resistance determines whether the rock will be removed.

$$S_R = S/R_R$$ **Equation 4.5**

where S_R is the stability ratio.

Example 1 S_R = (6768.1 Newtons)/(9205.8 Newtons)
= 0.74

Example 2 S_R = (9219.7 Newtons/(9205.8 Newtons)
= 1.00

Example 3 S_R = (11188.1 Newtons)/(9205.8 Newtons)
= 1.22

If the stability ratio is greater than 1, then the suction is greater than the block resistance and removal by suction can occur. If the stability ratio is less than 1, then the block resistance is greater and the block should remain in place (Figure 4.1), this is similar to the formula by Graf (1979) for large boulder movement. Example 2, where the velocity is 4.085m/sec represents the threshold velocity because the stability ratio is 1.00.

4.1.4 Concluding Remarks

Theoretically it has been shown that removal by lateral suction can occur. Since some of the forces are difficult to measure, the variability of the process can be explored experimentally. The following chapters will show that these forces can impact the current design of armourstone revetments leading to the removal of stones by suction.

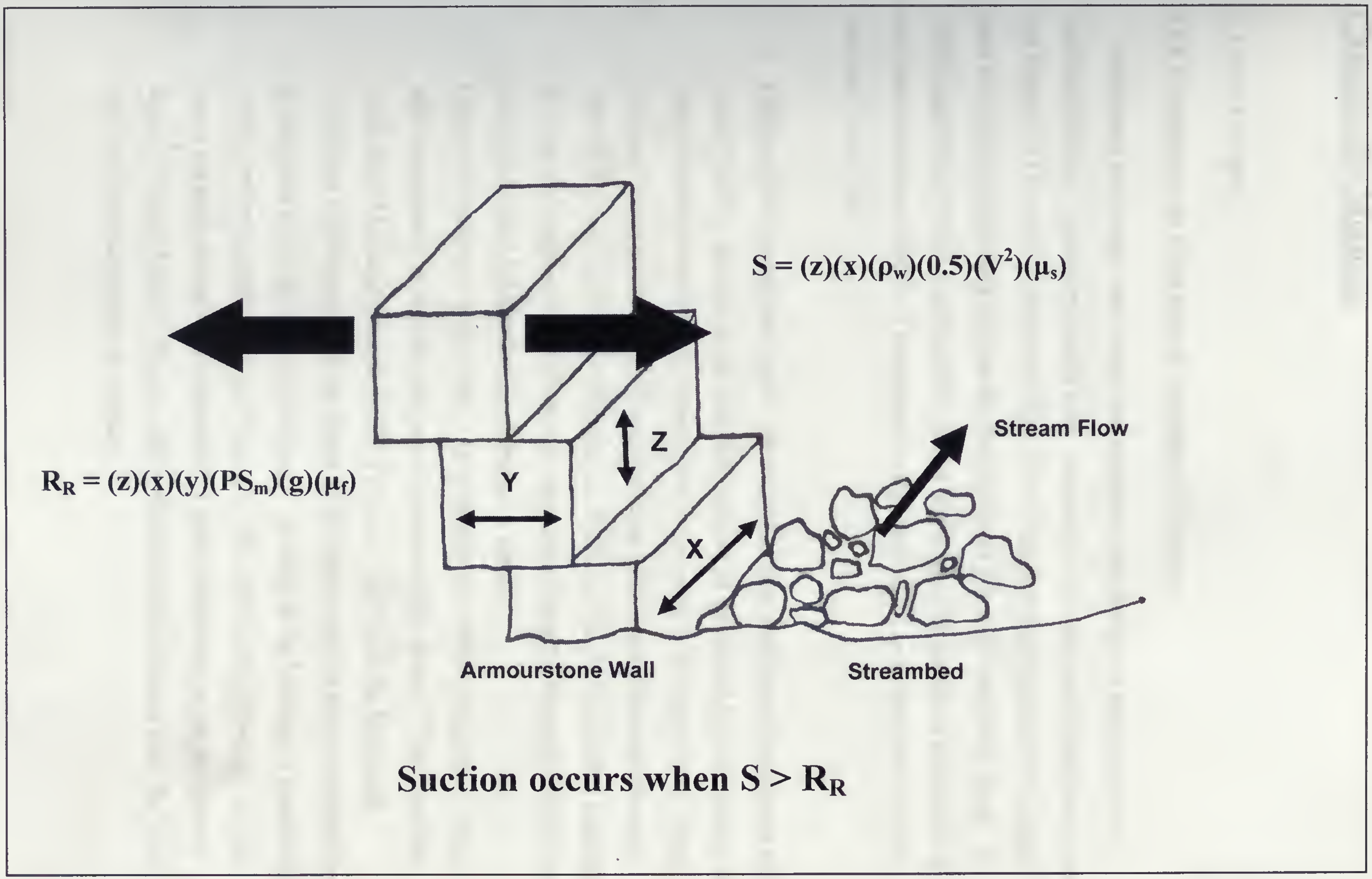

Figure 4.1 Diagram depicting the forces involved in the removal of armourstone blocks by suction. When suction is greater than rock resistance the block will be removed from the armourstone wall.

Chapter 5 – Methods

5.1 Field Work

5.1.1 Comparison of Field Sites to Maryland Guidelines

Mentioned previously were seven armourstone walls along five streams within Southern Ontario. These seven walls were compared to the Maryland Guidelines (2000) (see Figure 5.1) in order to determine if there were any similarities among the design of these armourstone walls and whether the design would allow for suction to occur. The criteria identified at these locations were based on the specific standards mentioned in the Maryland Guidelines (2000). The criteria chosen were based on ability to be seen and measured in the field.

1. Height of the armourstone wall - The height of bank stabilization structures are usually built to the top of the riverbank and can be controlled by such factors as stage duration; severity of overbank flow; how erodible the upper bank material is; type of bank protection used; and the slope of the bank (Biedenharn et al., 1997b). For armourstone revetments, the Maryland Guidelines (2000) state that the size of the stones used will be the controlling factor for the height of the wall and that the total height should not exceed 3 meters.
2. Length of the armourstones used - An armourstone wall is composed of stones which are placed so that the long axis is parallel to the stream. The size of the stone should be large enough so that it does not move and the Maryland Guidelines (2000) state that the length of the longest axis of the stone should be greater then 1/3 of the height of the wall. At each of the locations a number of stones were measured along the long axis. The stones were measured on two layers for each stream which consisted of either the bottom layer, the second layer, or the third layer. The two layers chosen for each stream were the layers that were most accessible to measure.

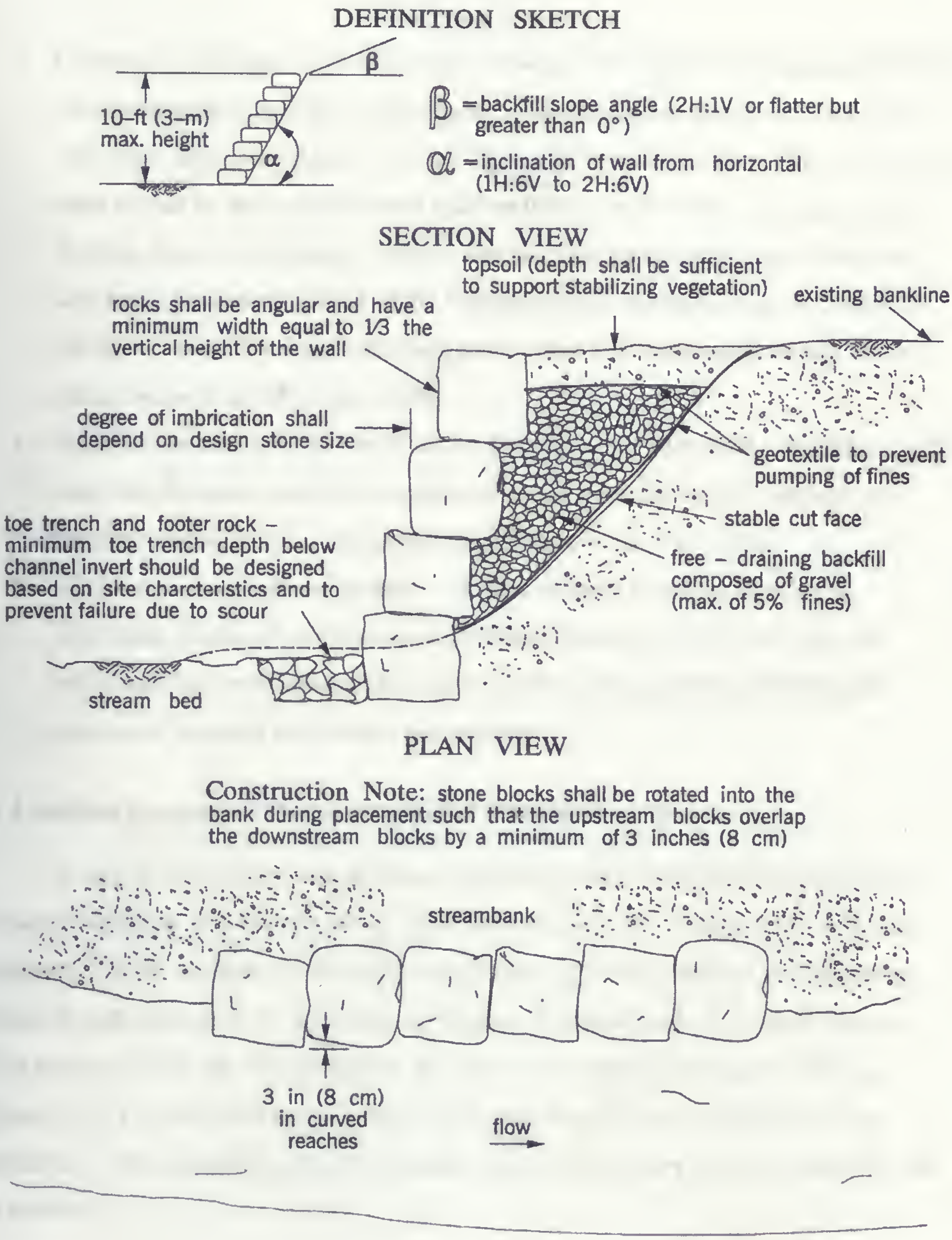

Figure 5.1 Design standards for armourstone revetments from the Maryland Guidelines. Where H and V represent the ratio of horizontal to vertical. Altered from the original source (Maryland Department of the Environment Water Management Administration, 2000).

3. Placement of the armourstones within the wall - The Maryland Guidelines (2000) refer to armourstone walls as imbricated riprap; therefore the stones used in the wall must have some degree of offset from one layer to the next. This seems to be done so that by the time the water reaches the top of the bank the energy of the flowing water is dissipated. Criteria that will also be checked are whether the wall has a planimetric offset, if the bottom layer of stones is lying on the bed or set into it, and if the stones are staggered so that the one stone is resting on two stones below it (as in a brick wall).
4. Shape of the armourstones used within the wall - The Maryland Guidelines (2000) state that the stones used in an armourstone revetment should be angular and blocky because it makes placement of the stone in the wall easier.
5. Additional structural components - At each of these locations there were additional structural components within the armourstone wall that were not mentioned by the Maryland Guidelines (2000) and are used to improve the stability of the wall and were noted as found.

5.1.2 Surface Roughness Measurements for Armourstone Blocks

A number of armourstone surfaces were measured to illustrate the variability of surface roughness. The surface of the stone was measured by laying a ruler across the block either in the vertical or horizontal direction along the top surface, stream facing surface or side surface of the armourstone blocks. Measurements were then made at 15cm intervals from the rock surface to the ruler to determine the length of the gap (Figure 5.2). For each surface and direction the mean and standard deviation were calculated. The armourstone sides that were measured depended on the accessibility of the surface.

5.1.3 Measurements of Gaps between Adjacent Upper Layer Stones

The gaps between the armourstone blocks along the top layer were measured along Forty Mile Creek before the wall was restored (Figure 5.3). These gaps occurred after the sediment had been removed from between the stones and were also due to the

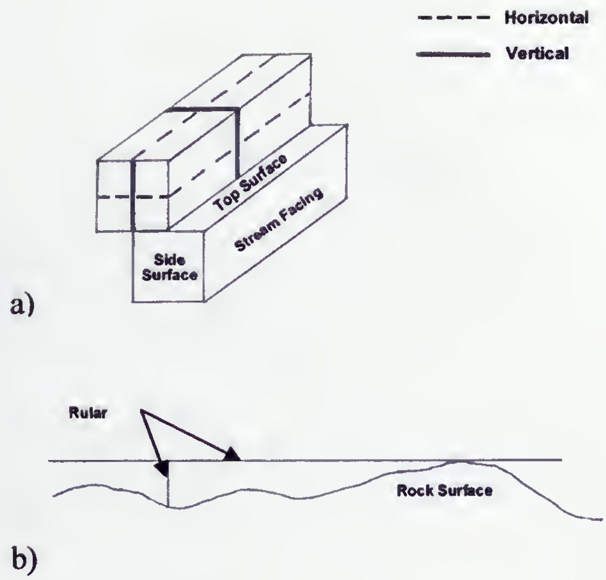

Figure 5.2 Displays graphically how the surface roughness was measured for each of the armourstone blocks. a) Illustrates how the ruler was laid upon the surface (horizontal and vertical direction). b) Illustrates a close up of the rock surface, where the length of the gap was measured.

Figure 5.3 One of the gaps measured between the armourstones along the wall at Forty Mile Creek, Grimsby. This gap was measured as a triangular prism.

fact that the stones are not perfectly rectangular. The gaps between the stones will allow water to remove the sediment therefore allowing water to surround the stone, which then influences the buoyant weight of the block. Depending on the shapes of adjacent stones the gaps were measured as either a triangular prism or cuboids so that the volume could easily be calculated. The volume of each of the gaps was calculated and combined for a total volume of gaps compared to the average total volume for the row.

5.1.4 Cross Sections Measured at Forty Mile Creek, Coronation Park Grimsby

In order to explore the hydraulic conditions at Coronation Park for Forty Mile Creek a number of cross sections were measured so that they could be entered into HEC RAS. For the 250m length of stream in this section, four cross sections were measured using a laser level and a surveyors' pole and were spread out throughout the entire length of the reach. From these four measured cross sections five more were interpolated from the data, providing a total of nine cross sections for an overall view of the creek. In order to determine the slope of the bed known spot heights from the two bridges that cross the upstream and downstream end of the stream were used and the distance from the bridge to the bed of the creek was subtracted. The difference in elevation from the upstream end to the downstream end is 4m for a length of approximately 250m, resulting in a slope of 0.016.

5.1.5 Hydraulic Variables Collected in the Field for Forty Mile Creek

Due to the close proximity of Forty Mile Creek it was easy to gather data after a period of intense rainfall or snow melt to determine the extent of flow velocities present adjacent to the armourstone wall. Flow velocities measured in the field are in m/sec. On the right hand side of the stream a stage gauge was marked on a tree so that depth measurements could easily be identified. After a period of intense rainfall approximately 10 hours was waited in order to try and catch the maximum discharge. During the fieldwork floats were used to determine the mean surface velocity by timing how long it took a stick to travel 10m downstream. The floats were thrown into the stream so that the surface velocity was measured close to the armourstone wall. From the surface velocity measurements the mean velocity of the sampled flow could be computed.

$V_s = L/T$ **Equation 5.1**

where V_s is mean surface velocity, L is distance, and T is time.

$V = V_s - V^*$ **Equation 5.2**

where $V^* = 2.5\sqrt{((g)(S_{chan})(d))}$ (Dingman, 1984)

where V is the mean velocity, g is the gravitational constant, S_{chan} is slope, d is depth and V^* is shear velocity.

Measuring the wavelength of a standing wave can also provide the velocity for the flow. The wavelength formula is:

$V = 1.25\sqrt{w}$ (Kennedy, 1963) **Equation 5.3**

where w is wavelength.

The Froude number was also calculated for each of the flows measured in the field. The formula for Froude number:

$Fr = V/\sqrt{(gd)}$ (Robert, 2003) **Equation 5.4**

5.1.6 Hydraulic Programs and Equations

To establish the suitability of stabilization structures for a particular stream engineers use hydraulic programs and equations, which are based on average flow velocities. To determine the hydraulic characteristics of a stream one-dimensional models using the standard step-backwater method are used. The cross sectional data that was collected during fieldwork for Forty Mile Creek was entered into the hydraulic program HEC RAS. The Town of Grimsby performed a floodplain analysis in 1990 (Bishop, (personal communication) 2003) for Forty Mile Creek and determined discharge and velocity for specific return periods (Table 5.1). The data was computed using the hydraulic program QUALHYMO and the discharge data was used for HEC RAS analysis.

Return Period (Years)	Peak Discharge (m^3/sec)	Velocity (m/sec)
2	9.73	1.87
5	12.60	2.01
10	14.60	2.11
20	16.60	2.19
50	19.30	2.34
100	21.40	2.44

Table 5.1 Results of a floodplain analysis showing discharge and velocity for specific return periods for Forty Mile Creek, Grimsby, Ontario (Bishop, personal communication, 2003).

Once this data was entered into HEC RAS numerous hydraulic variables could be calculated. Output is provided not only for the whole 250m section but also for individual cross sections. Panel velocities are also calculated for each of the cross sections, where HEC RAS displays the cross section showing the location and the mean velocity across the channel. Colour coded bars display the different velocities, showing in general where the fastest and the slowest estimated velocities are. Using the mean velocity for the panel and the maximum channel depth provided by HEC RAS, surface velocities can be estimated by using equation 5.2.

Equations are used not only to determine the hydraulic conditions of the stream, but they can also be used to determine the size of rock used as bank protection. In the armourstone design from the Maryland's Guidelines (2000) they mention the use of the Isbash Equation. The equation allows the engineer to determine the size of rock that can be used based on a given flow velocity.

$$Dc = C_1(\rho_w/(\rho_r-\rho_w))(V^2/2g)$$ (Carling and Tinkler, 1998) **Equation 5.5**

where Dc is stone size; C_1 is a coefficient which is equal to 1.35 for isolated or 0.69 for 'embedded' stones; ρ_w is the specific weight of water; ρ_r is the specific weight of rock; V is velocity; and g is the acceleration due to gravity.

A sample of armourstones in the field was measured to determine their nominal diameter so that this equation could be used to determine the velocities needed to move the stones.

5.2 Experimental Setup

Because it is possible for large blocks of rock to be lifted off the bed, it seems possible that this process could cause the removal of stones from the armourstone wall. If the water within the channel is deep enough to surround the stone and the velocity of water against the wall is fast enough the stone should be removed. The experiments described in this section were used to test the theory on whether it is possible for suction to remove these large stones away from the wall.

5.2.1 Flume

Experiments were performed in a re-circulating flume that is approximately 9.0m long, 0.62m wide and 0.51m deep to test the theory of removal of the stone due to suction (Figure 5.4). When using flumes for experimental work there are some problems regarding scaling, where some of the naturally occurring forces will ultimately be missing from the experimental work. It is possible to alter the hydraulic forces and materials from the natural conditions to best represent form and function of the experimental design (Thompson and Wohl, 1998). It is important to ensure that the Froude number (Equation 5.4) and Reynolds number represent the natural conditions within the flume and are realistic (Thompson and Wohl, 1998).

For this experimental work it was important to get the flow conditions similar to what can be expected in natural conditions. Field observations along the study reach show that at high flow the formation of standing waves occurs, indicating the Froude number is close to 1. Therefore the flow within the flume needed to be near critical (≈ 1) and this was achieved by the experimental setup. The experimental wall was setup along the right side of the channel and began at 2.85m downstream of the head box. The first 0.37m consisted of weighted stationary blocks that were used to protect the experimental wall from the force of water directly hitting it. Stationary blocks were also set up in behind the experimental wall, as well as at the end of it. These stationary blocks, which were flush to the wall and gaps sealed, prevented significant horizontal velocities from occurring behind the wall. The experimental wall was built with a curve of 8.13 degrees so that it constricted the channel. A large stone (0.74m long) was placed 2.20m

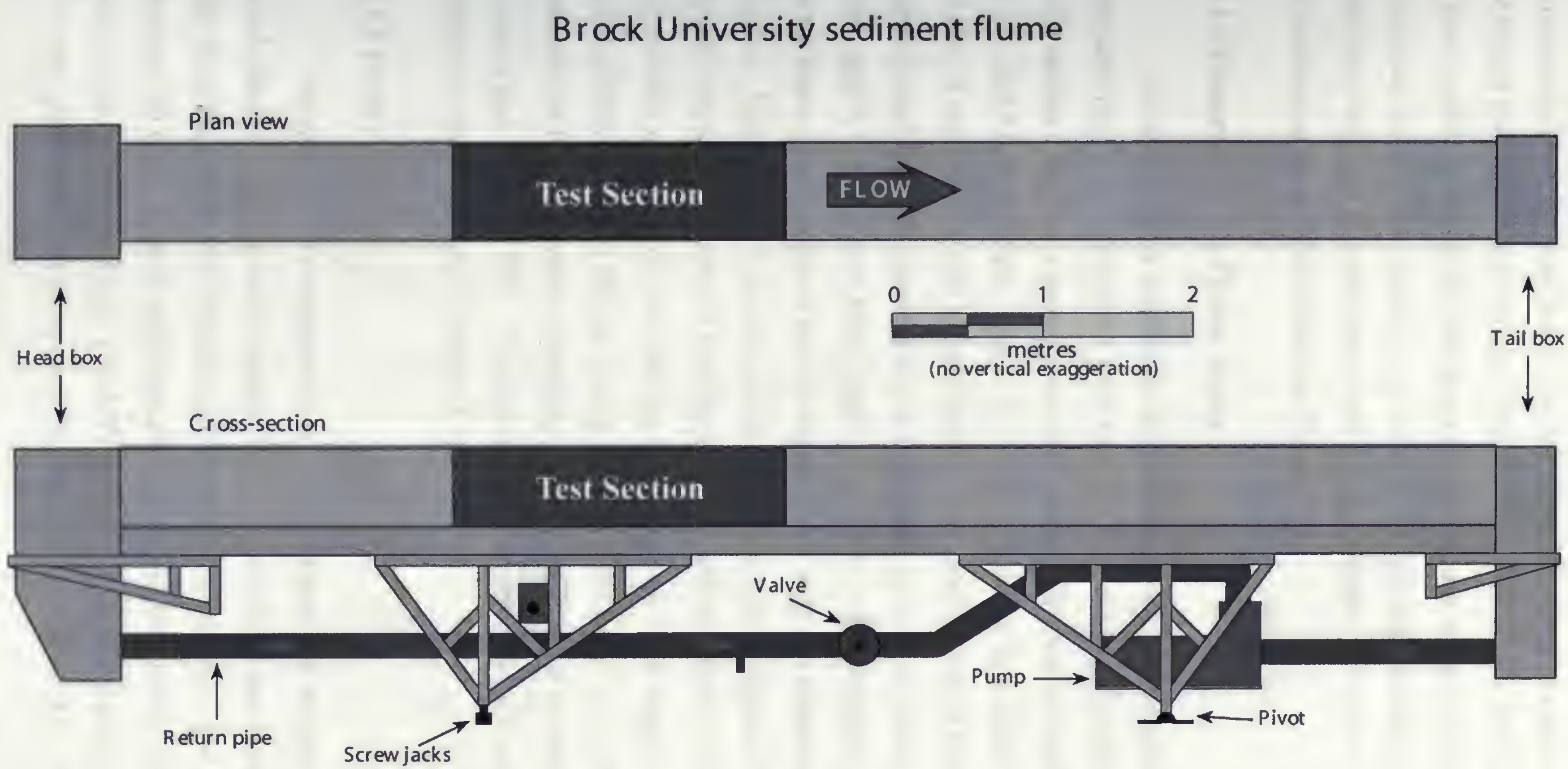

Figure 5.4 Re-circulating flume used for experimental work. Test section represents experimental setup area.

downstream from the head box on the left side of the channel and this caused the water to be forced towards the experimental wall and also reduced the width of the channel. These conditions forced the flow to accelerate through the experimental area and standing waves developed. The length of the entire setup was approximately 2.20m. The slope of the flume was kept constant throughout the experimental work at 0.013 which is similar to the slope at Forty Mile Creek (see Figure 5.5).

5.2.2 Properties of the Plaster blocks

The armourstone wall for the experimental work was represented by four blocks that were made out of Plaster of Paris (density was 1.65 g/cm^3) and were molded from milk cartons which gave approximate dimensions of 20.0cm in length, 6.0 to 7.0cm width, and 9.0cm in height. Due to the limited velocities achievable in the flume, the Plaster of Paris blocks with a lower density were used instead of blocks of rock. The experimental wall was spaced out over 0.89m and the 4 blocks were spaced so that there was a gap in between each block (approximately 3.0cm). Although sediment can be used in the flume, it was removed and the experimental wall was placed on top of the Plexiglas bottom. An experiment was done to determine the sliding friction of the block when the surface was wet. A Plaster of Paris block was placed on a sheet of Plexiglas that was misted with water and the one end was raised until the block began to slide. The result of this experiment showed that the average sliding friction was 0.56, with a standard deviation of 0.04; this value is the tangent of the angle and is normally used in equations (Carling and Tinkler, 1998). The sliding friction represents the friction value for the block resistance equation (Equation 4.3).

5.2.3 Probes

The majority of the experiments performed involved the determination of velocity within the flow. An Acoustic Doppler Velocimeter (ADV) was used to gather velocity data from the flow before it passed near the experimental wall. The ADV is able to measure 3D water velocity using one transmitter and three acoustic receivers to sense ambient particles in the flow. The ADV measures a small sampling volume 5cm away from the probe, with a velocity range programmable from +/- 3 to +/-250cm/s and obtains

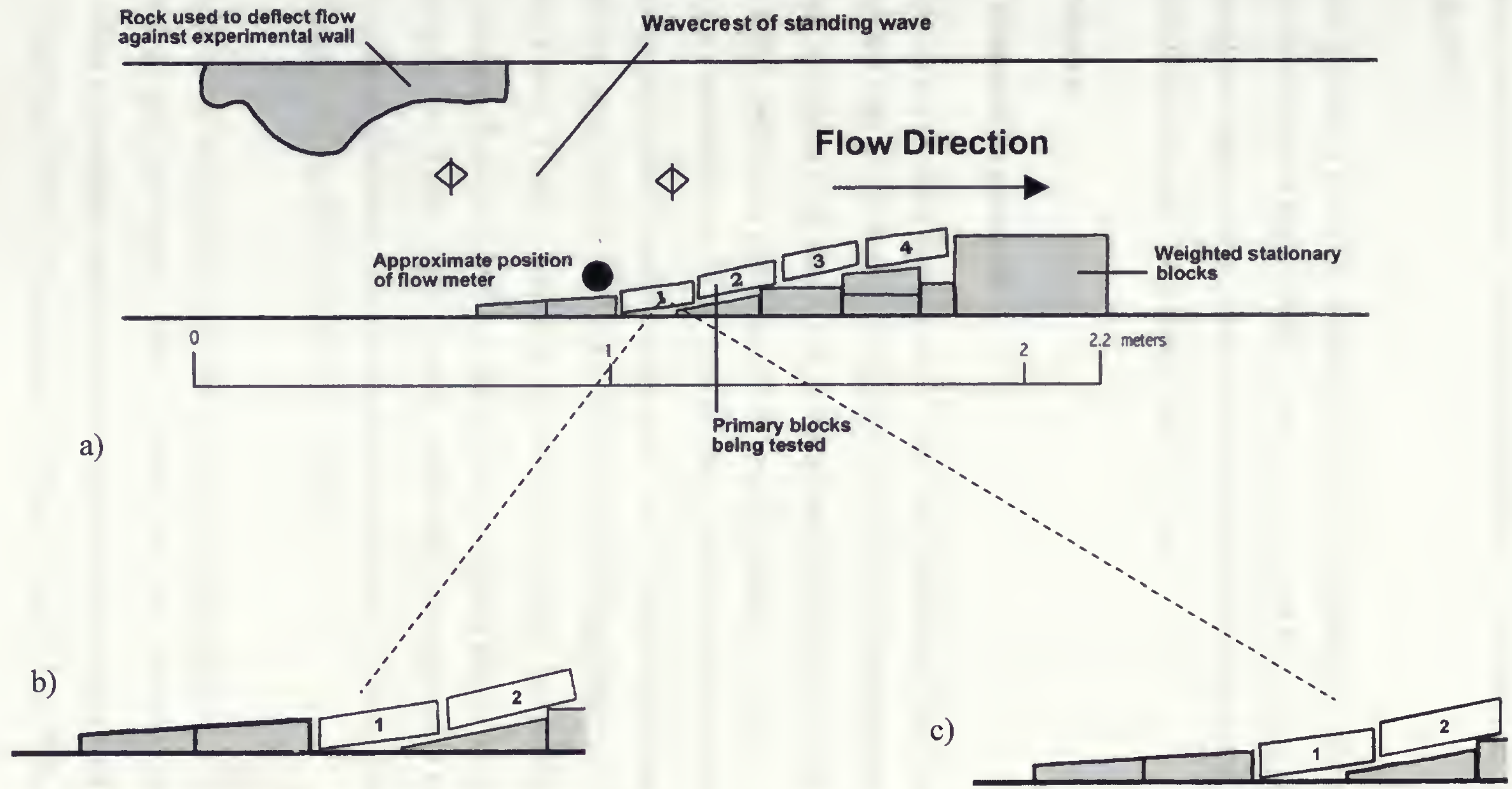

Figure 5.5 Flume setup for experimental work. a) Illustrates the entire experimental area. b) Illustrates a close-up of block #1 with 0 offset. c) Illustrates a close-up of block #1 with 2mm offset.

the data at a sampling rate up to 25 Hz. Each velocity measurement within a sample set is composed from an average number of pings, which is approximately 200 to 250 times per second depending on the specified sampling rate. The sampling volume is cylindrical and has a diameter of 6mm and a height of 9mm. Flow velocities are measured in orthogonal components, where X is parallel to the flow, Y is perpendicular to the flow, and Z is up and down.

Due to the size of the ADV it could not be used to determine the velocities in the gaps between the Plaster of Paris blocks. A two dimensional electromagnetic Marsh McBirney probe was used for this purpose, collecting point velocities at locations in the gaps. All velocities collected in the flume are in cm/sec.

5.3 Experiments

5.3.1 Block Removal Experiment

Preliminary tests were done to see at what water depth the block would be removed from the wall to determine the significance of block submergence. During the initial test runs it became clear that block removal was unpredictable, even though all conditions (layout, depth, and pump speed) remained apparently constant. Thus, it was decided that the experiment would be done in sets of ten for each of 6 static depths to determine which depth had the most blocks come out. The static depths are the flow depths within the flume when it was not running and the depths that were used were approximately 1.8cm, 2.8cm, 3.8cm, 4.8cm, 5.8cm, and 6.8cm. No blocks were removed during the 1.8cm depth due to low flow depths; also there was excessive surging of the flume discharge, so the 1.8cm depth was not used in the data analysis. The 2.8cm depth also caused the flume discharge to surge slightly but removal of blocks did occur and therefore this depth was described in the data analysis.

Each set of ten experiments was done twice for each depth, once with a 2mm offset for block #1 and once with no offset for block #1. The offset was used to test the planimetric offset in the design standards for armourstone walls suggested by the Maryland's Guidelines (2000). By altering the offset of block #1 the data could be

analyzed to determine whether the planimetric offset had any influence on the removal of the block.

Block movement was always consistent in the way that the block moved away from the wall. The movement of the block was a pivot, in which the upstream end of the block moved in towards the channel center first, normally swiveling and rotating the entire block 180° as it was carried away.

5.3.2 Movement Time for Block #1

The movement time for block #1 was calculated from the moment the upstream end of the block moved away from the wall to the moment it passed block #2. The data set that was analyzed were the runs for zero offset where block #1 was removed. This was done by using the timer on the clips from the video recordings. Averages and standard deviations were calculated for each of the five depths. The purpose of this experiment was to determine if the times were similar to the instantaneous velocity fluctuations mentioned in the research.

5.3.3 Sand Removal Experiment

To replicate the formation of large depressions found behind the top layer of stones in the field, an experiment was done to determine whether the flow of water could cause the removal of sediment by essentially the same flows that cause suction of the blocks. One was a medium to fine sand with a mean of 2.1φ and a sorting coefficient of 0.51φ, which is well sorted. The second was a coarse to medium sand with a mean of 1.8φ and a sorting coefficient of 0.40φ, which is also well sorted. The third sample was very coarse with a mean of -0.2φ and a sorting coefficient of 0.98φ, which is moderately sorted. Means and sorting coefficients were determined using the Folk and Ward graphical method. Each type of sediment was packed behind the wall and in between the Plaster of Paris blocks of the experimental wall.

5.3.4 Velocity Experiments

The probe was set up as close to the weighted stationary wall (upstream end) as possible, just before block #1 so that velocities could be recorded before the flow passed the experimental wall. The ADV recorded data at every tenth of a second, providing an extensive set of velocity data for every run. Once data was collected it was parsed into an Excel spreadsheet where the data could be analyzed to determine flow fluctuations.

Each of the velocity components (*X*, *Y*, *Z* orthogonal directions) were combined to get one velocity value in order to make analysis of velocity data easier. This value is referred to as the total velocity. The total velocity for each depth was calculated as shown in equation 5.6. The mean velocity for each run was calculated from the total velocity.

$$V_T = \sqrt{(X^2 + Y^2 + Z^2)}$$ **Equation 5.6**

5.3.5 Gap Velocities

The Marsh McBirney probe was used to collect velocity data in the gaps behind block #1 as well as in between block #1 and block #2. The probe measured the velocities in the X and Y direction and the experiment was done to verify that the velocities behind the experimental wall were much slower than the channel flow creating a pressure differential. Two static depths were chosen for this experiment, 4cm and 6cm. Once the data was collected it was also parsed into an Excel spreadsheet where the mean and standard deviation were determined, as well as the total velocity.

$$V_T = \sqrt{(X^2 + Y^2)}$$ **Equation 5.7**

5.3.6 Corner Block

Due to the fact that the upstream end of block #1 always moved first, velocities needed to be collected at this corner, which was not possible with the ADV probe. In order to do so a new block was designed and constructed (Figure 5.6). The design of the

block allowed velocity measurements to be computed because as the water entered the upstream end and collected in the tube, the height of the water was measured and the velocity head formula was applied (Dingman, 1984). A plaster block was cut diagonally through the longest length of the block. Three tubes were placed inside chiseled paths and then the block was glued together. The one end of the tube came out at the upstream end of the block and the other end of the tube came out at the top. Each tube at the upstream side exited the block at different heights. The heights of the tubing off the bed were 1.0 cm, 4.5 cm, and 7.0 cm; this allowed velocities to be calculated at different heights in the water profile. A fourth tube was used to determine the static pressure. The three static flow depths that were used for this experiment were 4.8 cm, 5.8 cm, and 6.8cm. The lower water depths were not used because the height of the water in the tube could not be read because they were below the top of the brick. Each of the water depths was run for approximately 5 minutes and each of the tubes was watched to determine the maximum height.

5.3.7 Other Velocity Measurements

Other methods to determine velocity within the experimental area were surface velocity, mean velocity from the wavelength of the standing wave, and the formation of erosional scallops. Surface velocity was measured in the flume using floats because the ADV could not measure surface velocities. Tens runs were conducted where the length of time taken by a piece of Styrofoam traveling 5m along the flume was recorded, using equation 5.1.

When the static depths of 4.8cm, 5.8cm, and 6.8cm were run in the flume a stationary wave formed beginning at the upstream stationary block and ending in front of block #1. Velocity for this area could then be calculated by measuring the wavelength and using equation 5.3.

Because the blocks used in the experimental wall were made of slightly soluble Plaster of Paris it was noticed towards the end of the experimental investigation that

Figure 5.6 Picture of the constructed tube block used to collect velocity data by measuring the water height in the tubes and using the velocity head formula.

scallops had formed on the channel side of the block. Scallops typically form in karst topography and can be used to determine flow velocity because the size is inversely related to the flow velocity that formed them (White, 1988). Although the use of scallop measurements was not planned, the scallops were measured to determine approximate flow velocity along the wall of block #1. Scallop formation is controlled by the fluid layer adjacent to the wall (White, 1988); therefore the velocity against the experimental wall can be determined by the scallop size.

Chapter 6 – Results

This chapter will provide the results from both field and experimental work. The first section will discuss the design characteristics for the seven armourstone walls studied in the field; the second section will provide hydraulic data for Forty Mile Creek; and the third section will discuss the results determined by the experimental work in the flume.

6.1 Field Work

Design similarities of the seven walls to the Maryland Guidelines (2000) and design criteria that may allow for suction to occur are summarized below.

6.1.1 Height of the Wall

Table 6.1 shows the data collected relating to the height of each of the walls within the study areas. Each of the seven locations follows the Maryland's standards in that all of them are not higher then 3 meters. Although the majority of the walls are at least 3 stones high, the height of the individual stones is obviously kept below a meter, therefore keeping the overall height below 3 meters.

The location of the wall also seems to dictate the height of the structure. When the armourstone wall was located on the outer bank of a stream bend the revetment is higher then it was for walls along straight reaches. The wall with the shortest height was located along Loyalist Creek and this wall lined a large distance of the streambank.

6.1.2 Length of Armourstones Used

All of the armourstone walls studied were built so that the long axis of the stone is parallel to the stream. Tables 6.2 to 6.4 show the statistical information for the stone length on the different layers for the armourstone walls. All of the streams show that on average, the length of the stones are over 1m, but when looking at the maximum and minimum lengths it can be seen that there is quite a broad range of sizes. Also, all of the

walls show that on average the length of the stone is greater than 1/3 the height of the wall. Some of the creeks also show that on average the larger stone is placed along the bottom with the smaller one on top.

Location	Maximum Height of Wall (m)	Number of Stones in a Column	Location of the Wall
Forty Mile Creek	Approximately 2.5 to 3.0	Upstream end is 3, then 2, then 1	On the outside of a stream bend
Tuck Creek	Approximately 2.25	3	On the outside of a stream bend
Appleby Creek	Approximately 2.0	Upstream end is 3, then 2	Along a straight section on one side of the channel
Cooksville Creek at Robert Speck	Approximately 2.0 to 2.5	The majority of the wall is 3, but some spots are 2	Lines both sides of the channel, fieldwork was done along a straight section
Cooksville Creek at Mississauga Valley	Approximately 2.30	3	Lines a short, straight section
Cooksville Creek at Aqua	The outside bend is approximately 2.8	Most of the outside bend is 4 high, some spots are 3 and the inside bend is 2	Lines both sides of the bank along a stream bend
Loyalist Creek at Thorn Lodge	Approximately 1.50 to 1.85	2	Lines both sides of the channel for a large distance, fieldwork was done along a straight section

Table 6.1 Fieldwork sites and data relevant to the height of the armourstone wall.

Location	Bottom Layer Average Length of Long Axis (m)	Bottom Layer Standard Deviation (m)	Bottom Layer Maximum Length of Long Axis (m)	Bottom Layer Minimum Length of Long Axis (m)	1/3 of the Height of the Armourstone Wall (m)
Tuck Creek	1.41	0.28	1.80	1.05	0.75
Appleby Creek	1.25	0.47	2.30	0.70	0.66
Cooksville Creek at Mississauga Valley	1.45	0.36	2.21	0.95	0.76
Cooksville Creek at Aqua	1.57	0.34	2.20	1.00	0.93
Loyalist Creek at Thorn Lodge	1.39	0.44	2.45	0.90	0.50

Table 6.2 shows data regarding the length of the long axis of the stones on the bottom layer of the armourstone wall for some of the streams. On average all of the stones are above 1 meter, but there is a large range between the maximum and minimum stone lengths. All locations have stones that have a long axis that are larger than 1/3 the height of the wall.

Location	Second Layer Average Length of Long Axis (m)	Second Layer Standard Deviation (m)	Second Layer Maximum Length of Long Axis (m)	Second Layer Minimum Length of Long Axis (m)	1/3 of the Height of the Armourstone Wall (m)
Forty Mile Creek	1.66	0.25	2.15	1.20	0.83
Tuck Creek	1.54	0.45	2.35	0.90	0.75
Appleby Creek	1.45	0.63	2.43	0.65	0.66
Cooksville Creek at Robert Speck	1.35	0.44	2.28	0.77	0.66
Cooksville Creek at Aqua	1.47	0.48	2.50	0.66	0.93
Loyalist Creek at Thorn Lodge	1.21	0.31	1.83	0.75	0.50

Table 6.3 shows data regarding the length of the long axis of the stones along the second layer of the wall. Again, all of the stones on average are well above 1 meter in length, but there is still a large range between the maximum length and the minimum length. Appleby Creek and Cooksville Creek at Aqua Drive have minimum lengths that are lower than 1/3 the height of the wall.

Location	Third Layer Average Length of Long Axis (m)	Third Layer Standard Deviation (m)	Third Layer Maximum Length of Long Axis (m)	Third Layer Minimum Length of Long Axis (m)	1/3 of the Height of the Armourstone Wall (m)
Forty Mile Creek	1.45	0.30	2.00	1.09	0.83
Cooksville Creek at Robert Speck	1.33	0.29	1.73	0.90	0.66
Cooksville Creek at Mississauga Valley	1.16	0.20	1.41	0.87	0.76

Table 6.4 shows data regarding the length of the long axis of the stones on the third layer of the wall for some of the streams. Again, on average all of the lengths are above 1 meter but there is still a large range between the maximum and minimum lengths. All locations have stones that have a long axis that are larger than 1/3 the height of the wall.

6.1.3 Placement of Stones

Vertical offset was identified at all of the locations and the amount was measured for each stone on one layer. Tables 6.5 and 6.6 show the average offset for either the bottom layer to the second layer or the second layer to the top layer.

Location	Average Offset from Bottom to Second Layer (cm)	Standard Deviation (cm)
Tuck Creek	29.2	7.7
Appleby Creek	25.6	6.8
Cooksville Creek at Aqua	31.8	12.0
Loyalist Creek at Thorn Lodge	26.1	12.0

Table 6.5 Amount of vertical offset for the bottom layer to the second layer of stones for some of the field locations.

Location	Average Offset from Second Layer to Top Layer (cm)	Standard Deviation (cm)
Forty Mile Creek	33.5	9.9
Cooksville Creek at Robert Speck	20.4	9.9
Cooksville Creek at Mississauga Valley	39.6	5.8

Table 6.6 Amount of vertical offset for the second layer to the top layer of stones from some of the field locations.

Each of the site locations is fairly similar to the other locations, but there does seem to be some inconsistency at the individual sites according to the standard deviations. The Maryland Guidelines (2000) also suggest the wall should have a planimetric offset with the upstream stone overlapping the downstream stone by a minimum of 8cm in curved reaches (refer to Figure 5.1). None of the streams have a specific planimetric offset for the armourstone walls. Some of the streams had downstream blocks sticking out further then upstream blocks and some also seem to have had no offset at all.

The Maryland Guidelines (2000) also suggest that each stone should be resting on two stones below it so that their joints are staggered (as in a brick wall), Figure 6.1. There was partial staggering of the stones along some of the walls, but for the most part it did not occur. This is due to the fact that the stones are all different sizes, therefore smaller stones will not be able to rest on two stones below it.

All of the armourstone walls within the field study, except for Forty Mile Creek seem to have the stones resting on top of the bed. The wall along Forty Mile Creek has a bottom layer of stone which is inset into the streambed.

6.1.4 Stone Shape

In general the stones have a rectangular shape in the sense that they have a long, intermediate, and a short axis, but the stones are not equant and the surfaces are not flat. This causes problems when the stones are laid on top of each other because they can not be placed tightly together. This leads to large gaps being present between adjacent stones and is common to all the armourstone revetments found during fieldwork (Figure 6.2). The presence of these gaps at the top of the structure seems to be the cause of large depressions that can be found between the bank and the stone. Before the wall at Forty Mile Creek was restored, as well as along Cooksville Creek large depressions were easily identifiable behind some of the top stones (refer to Figure 3.22). It was seen during high flows in Forty Mile Creek that the water was able to get in between the blocks, which would lead to removal of the sediment in behind the stone over time (Figure 6.3). The removal of the sediment in behind would therefore make it easier for water to surround the stone and therefore contribute to failure.

6.1.5 Additional Structural Components

The most common additional structural component was to use smaller pieces of angular stone (riprap) in combination with armourstone (Figure 6.4). The riprap is used to fill in void spaces between adjacent stones within the wall. The only locations that seemed to have very little if any riprap, were those found along Cooksville Creek. Another material that was used for this same purpose was grout. Appleby Creek and Cooksville Creek at Robert Speck had parts of the wall where grout was used to fill in the void spaces. Vegetation can also be added to armourstone walls to improve the stability and it is most commonly live staking that is planted. Vegetation was only seen along the Mississauga Creeks and was planted at the top of the streambank. The placement of vegetation is along the top part of the bank so that it helps to prevent the loss of soil from behind the stones. Along Loyalist Creek in Mississauga another type of structural feature

Figure 6.1 Section of the armourstone wall along Forty Mile Creek, Grimsby, Ontario. This section shows how the stones can be staggered (as in a brick wall) so that they are resting on two stones below.

Figure 6.2 Section of Loyalist Creek, Mississauga, Ontario. The stones used in armourstone walls are of variable shapes and sizes which lead to the presence of large gaps.

Figure 6.3 Forty Mile Creek Grimsby, Ontario. At high water stages water can be seen in between the stones, which lead to sediment removal.

Figure 6.4 Forty Mile Creek Grimsby, Ontario. Riprap (small stones) is used in between the armourstone blocks to fill in the gaps.

was seen. Armourstone blocks were placed on the bed so that they were adjacent to the actual armourstone wall (Figure 6.5). It is believed that this was done to direct the flow of water away from the toe if the bank and to provide additional support for the wall.

6.1.6 Summary of Field Sites compared Maryland Guidelines

Even though the Maryland Guidelines (2000) were the only standards found during research there were a lot of similarities to the walls found in the field. Although these walls do show some design adaptations (vegetation, riprap, and grout) to combat common failures and to improve the stability of the wall. There are some design features that leave the wall susceptible to suction, specifically the placement of the armourstones so that the long axis is parallel to the stream, and the variable shapes and sizes of the stones that cause gaps between them.

6.1.7 Surface Roughness Measurements for Armourstone Blocks

The average and standard deviation for surface roughness of the armourstone blocks are mentioned in Table 6.7. It can be seen that there is a large standard deviation for each of the measurements for each of the surfaces, reinforcing the difficulty of determining a value for friction. This indicates that there is a wide range for surface roughness for each of the armourstone blocks.

Surface Location	Vertical Mean (cm)	Vertical Standard Deviation (cm)	Horizontal Mean (cm)	Horizontal Standard Deviation (cm)
Stream facing	2.00	2.97	2.42	2.85
Top	1.31	1.55	2.16	3.75
Side	3.62	4.27	2.96	2.93

Table 6.7 Surface roughness measurements for the stream facing, top, and side surfaces of the armourstone block. There is a large standard deviation for each of the sides indicating a wide range of surface roughness.

6.1.8 Measurements of Gaps between Adjacent Upper Layer Stones

The size of the gaps was measured so that volume could be calculated as either a triangular prism or cuboids. In total, 15 gaps were measured, from the downstream end

of the armourstone wall to approximately the 40m length of the wall (Table 6.8). The upstream 15m did not appear to have significant gap sizes present.

Gap Volume Triangular Prism (m^3)	Gap Volume Cuboids (m^3)
0.18	0.02
0.03	0.10
0.05	0.03
0.07	0.04
0.21	0.07
0.23	
0.11	
0.03	
0.01	
0.01	

Table 6.8 Volume of gaps between adjacent top layer stones at Forty Mile Creek based on either triangular prisms or cuboids.

The total volume of gaps in between adjacent top layer stones is 1.20m^3 compared to a total volume of the top layer of stones (55m length) which is approximately 35.00m^3. Gaps make up 3.43% of the top layer of stones (just in between the stones and not below). The gaps between the stones illustrate that the stones are not tight together, which could easily allow the blocks to be removed.

6.2 Hydraulic Data for Forty Mile Creek

6.2.1 Field Data

A total of nine surface velocities were collected from field work, the highest surface velocity will be mentioned here and the other raw data can be found in appendix B. The surface velocities were measured at the upstream end of the armourstone wall for a distance of 10m. Using Equations 5.1 and 5.2 the mean surface velocity and mean velocity of the sampled flow were calculated. Using Equation 5.4 the Froude number was calculated (Table 6.9).

Summary of Velocity Data Collected on March 5, 2004			
Mean Surface Velocity m/sec	**Shear Velocity m/sec**	**Mean Velocity of Sampled Flow m/sec**	**Froude Number**
3.19	0.66	2.53	1.04

Table 6.9 Velocity data collected in the field at Forty Mile Creek on March 5, 2004.

This data was collected on March 5, 2004 and the mean velocity of sampled flow was 2.53m/sec with a Froude number of 1.04 (Figure 6.6). The discharge for this event is similar to the 2 and 5 year return period in the floodplain analysis in Table 5.1. When the field velocities are compared to the velocities in Table 5.1 it can be seen that they are significantly different.

Velocity Data Collected on November 29, 2003		
Mean Surface Velocity m/sec	**Mean Velocity of Sampled Flow m/sec**	**Velocity Determined by Wavelength m/sec**
1.97	1.41	1.76

Table 6.10 Velocity data collected in the field at Forty Mile Creek on November 29, 2003.

Wavelengths were measured on November 29, 2003 where the surface velocity was 1.97m/sec and the mean velocity of the sampled flow was 1.41m/sec (Table 6.10). The wavelengths during that period were approximately 2m in length providing a flow velocity of 1.76m/sec (Equation 5.3).

Surface velocities collected in the field show that velocities can get higher than those determined by the floodplain analysis in Table 5.1.

6.2.2 HEC RAS Data

Hydraulic programs like HEC RAS determine average velocities within the profile. Since surface velocities are higher, it is possible to use the data provided by HEC RAS to determine the possible surface velocity. The cross section adjacent to the

Figure 6.5 Loyalist Creek Mississauga, Ontario. Armourstone blocks are placed on the streambed adjacent to the wall.

Figure 6.6 Forty Mile Creek Grimsby, Ontario. Picture taken on March 5, 2004 and was the highest surface velocity measured during fieldwork. Flow direction is from the bottom to the top.

location where the armourstones were removed by the flow, surface velocity can be calculated (Figures 6.7 and 6.8). Using the ten year return discharge, HEC RAS computed an average velocity for the cross section of 1.45m/sec and the panel velocity closest to the wall is 2.0m/sec. Using Equation 5.2:

$$V^* = 2.5\sqrt{(9.81\ m/sec^2)(0.016)(2.38\ m)} = 1.52\ m/sec$$

$$2.0\ m/sec = V_s - 1.52\ m/sec$$

$$V_s = 3.52\ m/sec$$

where V^* is the shear velocity, and V_s is the surface velocity.

By using this equation it can be seen that the surface velocity is much higher than the average velocity computed for the panel by HEC RAS. This value is also important because it is most likely the top armourstone that gets 'sucked out' first, so surface velocities are a significant component of it and by using the mean velocity for the flow profile as an index of stability can be very misleading.

6.2.3 Hydraulic Equations

A sample of armourstones was measured in the field to determine their nominal diameter (refer to Figure 6.9). The average nominal diameter worked out to be 93.0cm. Rearranging the Isbash equation (Equation 5.5) the velocities needed to move these stones would be on average 4.65m/sec, but none of the return period velocities in Table 5.1 are anywhere near this high. One must take into consideration the fact that the velocities in Table 5.1 are based on averages and that surface velocities and velocity fluctuations could be substantially higher. The stone size in the equation is based on the nominal diameter, but for the process of suction the specific lengths and orientation of the x, y, z planes are important. This leads to the conclusion that the Isbash equation does not represent the components needed to remove a block away from a wall by the process of suction.

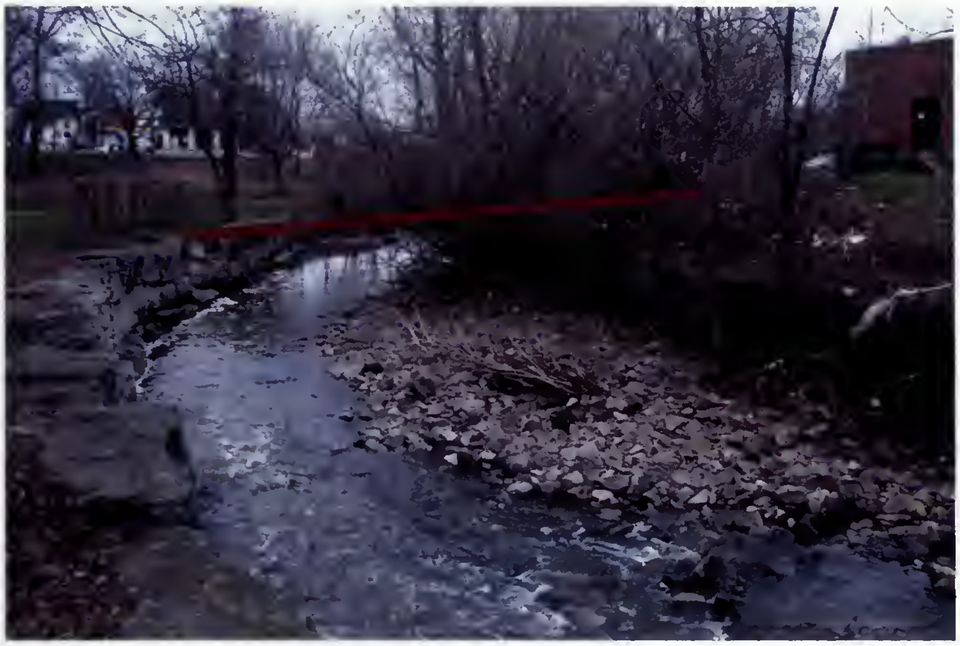

Figure 6.7 Forty Mile Creek Grimsby, Ontario. Picture showing the location of cross section #5 used in HEC RAS (indicated by the red line). HEC RAS cross section for this area is pictured below. Picture is looking downstream.

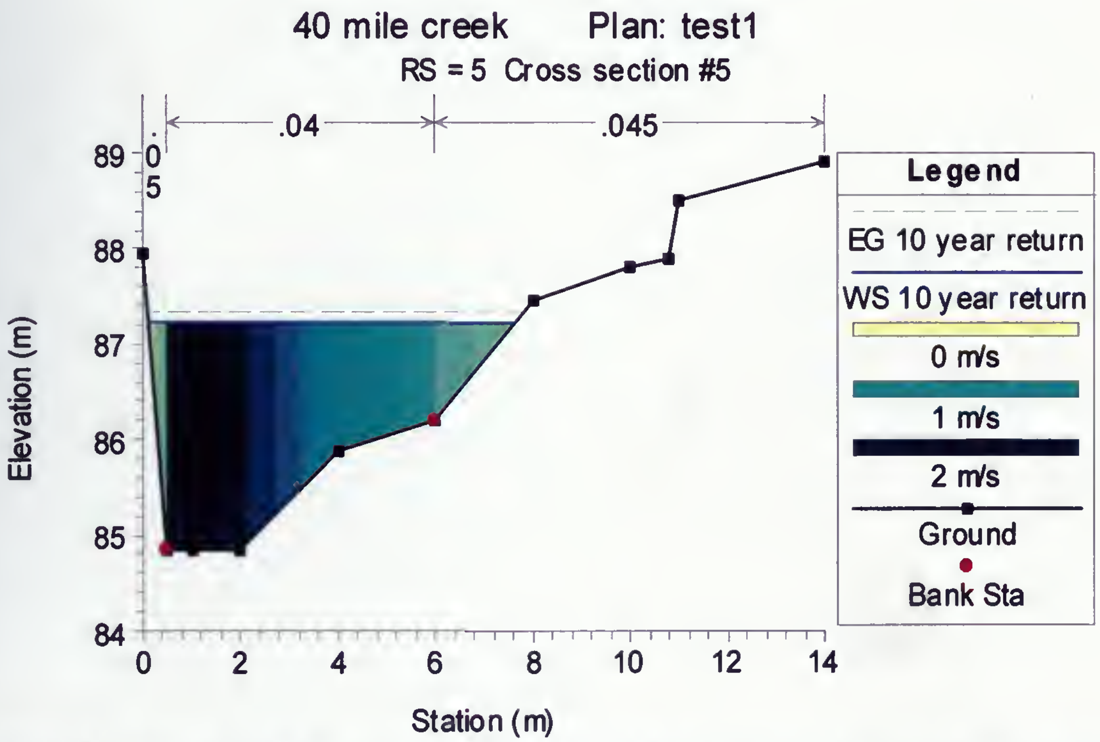

Figure 6.8 Diagram showing the cross section adjacent to where the stones were removed along Forty Mile Creek (cross section #5 pictured above). Panels indicate that velocities adjacent to the wall for the 10 year return are approximately 2m/sec.

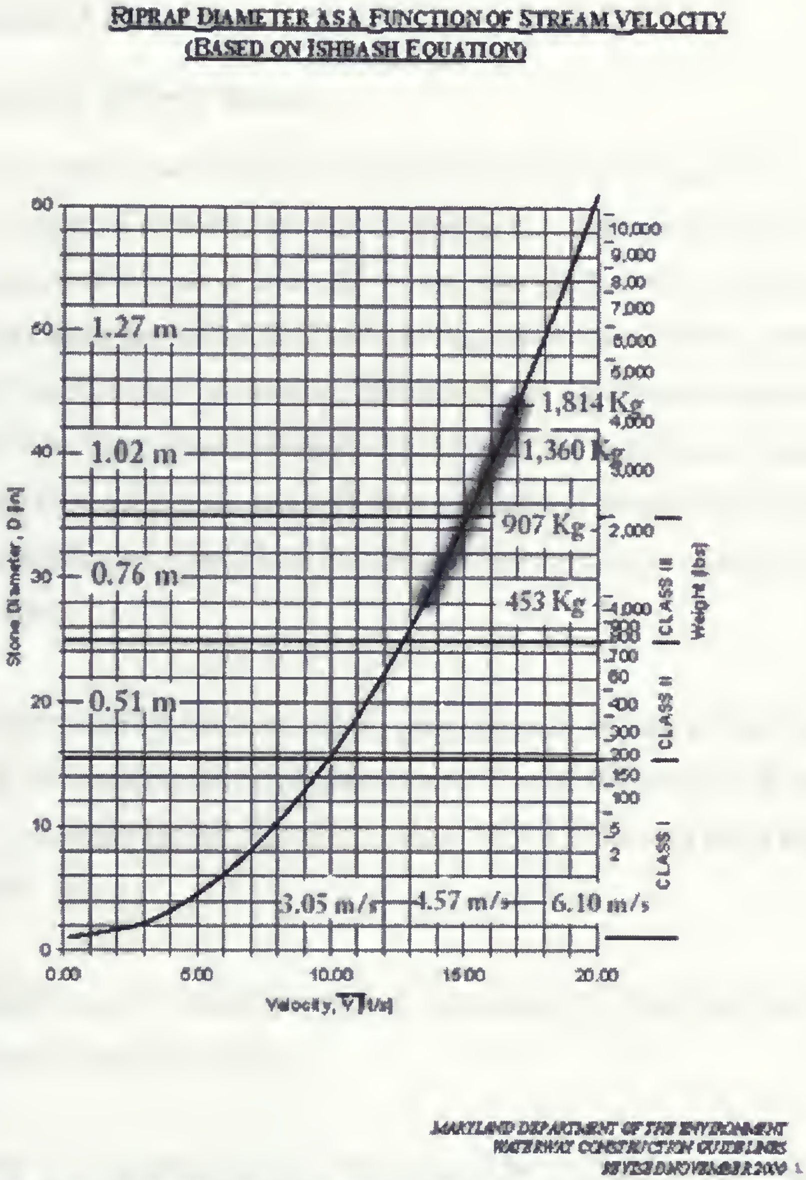

Figure 6.9 Diagram showing the relationship between stone size, velocity, and weight using the Isbash equation. Thicker line represents the location where sampled stone sizes fall indicating the need of 4 to 5m/sec flow velocities to move them. Modified from the original source (Maryland, 2000).

6.3 Experimental Results

6.3.1 Determination of Block Removal

The following results were obtained during the block removal experiment. Table 6.11 shows the sequence of block removal, as well as how many times a block was removed from the wall for each run of each depth. The block always pivotted away from the wall, with the upstream end of the block moving towards the channel center first. For the zero offset it was difficult to remove a block from the experimental wall at the lower depths, where as the 2mm offset had approximately half the runs have a block come out. Refer to Figures 6.10, 6.11, 6.12, and 6.13 for a sequence of pictures showing the block removal for a specific run. The depths that had the highest number of runs where blocks were removed were:

1. The 6.8cm depth for the 2mm offset, where 8 out of 10 runs a block was removed.
2. The 6.8 cm depth for the zero offset, where 7 out of 10 runs a block was removed.
3. The 5.8 cm depth for the zero offset, where 10 out of 10 runs had a block removed.

Overall, it took 28 out of 50 runs for a block to be removed for the 2mm offset and it took 24 out of 50 runs for the zero offset.

Block #1 was almost always the first block to be removed, except when block #4 came out by itself, which only occurred in 3 out of 100 runs. Neither block #2 nor block #3 came out by themselves, which suggests that their stability depended on block #1. It was unexpected that block #4 would come out by itself, but since the flow was directed along the wall it could indicate that flow velocities were potentially high enough along the entire wall to remove a block.

The depth of water in the flume as it was running was monitored for each run at each of the depths. The height of the block is 9cm and for each run the depth was monitored to determine how much of the block was submerged with water (Table 6.12).

Sequence of Blocks Removed from "Wall"

Legend
Order of Movement
First
Second
Third
Fourth

Depth of flume not running is 8.8cm
Offset is 2mm

	Block 1	Block 2	Block 3	Block 4	Total blocks removed for run
Run 141					4
Run 142					0
Run 143					0
Run 144					1
Run 145					1
Run 146					2
Run 147					1
Run 148					1
Run 149					2
Run 150					2
Total each block was removed	8	3	1	2	

Depth of flume not running is 8.8cm
Offset is 0

	Block 1	Block 2	Block 3	Block 4	Total blocks removed for run
Run 131					0
Run 132					1
Run 133					0
Run 134					2
Run 135					0
Run 136					3
Run 137					4
Run 138					1
Run 139					1
Run 140					1
Total each block was removed	7	2	1	3	

Depth of water in flume not running is 5.8cm
Offset is 2mm

	Block 1	Block 2	Block 3	Block 4	Total blocks removed for run
Run 81					3
Run 82					0
Run 83					1
Run 64					0
Run 85					4
Run 66					3
Run 87					0
Run 68					1
Run 69					0
Run 70					0
Total each block was removed	3	2	2	5	

Depth of water in flume not running is 5.8cm
Offset is 0

	Block 1	Block 2	Block 3	Block 4	Total blocks removed for run
Run 121					4
Run 122					1
Run 123					4
Run 124					4
Run 125					1
Run 126					4
Run 127					4
Run 128					4
Run 129					4
Run 130					1
Total each block was removed	9	8	8	9	

Depth of water in flume not running is 4.7cm
Offset is 2mm

	Block 1	Block 2	Block 3	Block 4	Total blocks removed for run
Run 31					1
Run 32					4
Run 33					0
Run 34					0
Run 35					0
Run 36					0
Run 37					1
Run 38					3
Run 39					4
Run 40					4
Total each block was removed	5	4	3	5	

Depth of water in the flume not running is 4.8cm
Offset is 0

	Block 1	Block 2	Block 3	Block 4	Total blocks removed for run
Run 111					4
Run 112					0
Run 113					4
Run 114					0
Run 115					0
Run 118					0
Run 117					0
Run 118					0
Run 119					0
Run 120					0
Total each block was removed	2	2	2	2	

Depth of water in flume not running is 3.7cm
Offset is 2mm

	Block 1	Block 2	Block 3	Block 4	Total blocks removed for run
Run 41					3
Run 42					0
Run 43					0
Run 44					4
Run 45					1
Run 46					4
Run 47					1
Run 48					0
Run 49					0
Run 50					0
Total each block was removed	5	3	2	3	

Depth of water in flume not running is 3.8cm
Offset is 0

	Block 1	Block 2	Block 3	Block 4	Total blocks removed for run
Run 101					0
Run 102					0
Run 103					0
Run 104					0
Run 105					0
Run 106					0
Run 107					2
Run 108					0
Run 109					0
Run 110					4
Total each block was removed	2	2	1	1	

Depth of water not running in the flume is 2.8cm
Offset is 2mm

	Block 1	Block 2	Block 3	Block 4	Total blocks removed for run
Run 51					1
Run 52					0
Run 53					0
Run 54					0
Run 55					1
Run 56					1
Run 57					1
Run 58					0
Run 59					0
Run 60					0
Total each block was removed	4	0	0	0	

Depth of water not running in the flume is 2.8cm
Offset is 0

	Block 1	Block 2	Block 3	Block 4	Total blocks removed for run
Run 91					0
Run 92					0
Run 93					0
Run 94					0
Run 95					0
Run 96					0
Run 97					1
Run 98					1
Run 99					1
Run 100					0
Total each block was removed	3	0	0	0	

Table 6.9 Sequence of block removal for each of the runs, as well as the number of times a block was removed from the wall for each run of each depth.

Figure 6.10 Clip 1 of a sequence of photos taken for an experimental run. The initial depth of the flume is 5.8cm and there was no offset. This is the initial position of the blocks, which are marked with red numbers, before block #1 (top of photo) began to move. Larger arrows are highlighting the crests of standing waves. Smaller arrow is highlighting the location of the ADV. Flow is moving from the top of the photo to the bottom.

Figure 6.11 Clip 2 of the same experimental run. This clip is 0.18sec after Figure 6.10, it can be seen that the upstream end of block #1 has begun to move away from the wall (pivoting), indicated by arrow.

Figure 6.12 Clip 3 of the same experimental run. This clip is 0.70sec after initial movement from the wall and it can be seen that the upstream end of block #1 has completely been removed from the wall.

Figure 6.13 Clip 4 of the experimental run. This clip is 0.85sec after initial movement from the wall and is now swept away by the flow.

Static Depth	2 mm Offset Average Water Depth (cm)	Zero Offset Average Water Depth (cm)	Degree of Submergence
2.8cm	7 to 8.5	5.95 to 8.59	Partially submerged
3.8cm	8.8 to 9.3	7.8 to 9.3	Partially submerged
4.8cm	10.1 to 10.2	9.3 to 9.9	Completely submerged
5.8cm	10.2 to 11.3	10.5 to 11.6	Completely submerged
6.8cm	10.6 to 11.7	10.5 to 11.6	Completely submerged

Table 6.12 Average water depth for each static depth and whether the block was totally or partially submerged.

Although blocks were removed at each of the static depths, it does seem that the set that had the most blocks come out was the more submerged set, which influences the block resistance (Equation 4.3).

The time it took for a block to be removed from the wall from the beginning of the experimental run is shown in the Figure 6.14. Generally, for both the 2mm offset and the zero offset, time decreased as depth increased. So the deeper the water the less amount of time it took to remove the block from the experimental wall. There are some depths were the removal time varied from less than a minute to more than two minutes. Most of the time the block came out quickly, but sometimes it moved slightly and then came out seconds later. The variability in removal time could be explained by velocity fluctuations within the flow, in which significant velocities to remove the block may need time to appear.

6.3.2 Movement Time for Block #1

The time that the upstream end of block #1 initially moved away from the wall to the time it passed block #2 was determined using the timer on the video recording clip. This was done for the runs in the zero offset where block #1 moved. Table 6.13 shows the mean and standard deviation for each of the five static depths.

Initial Depth (cm)	Mean (seconds)	Standard Deviation (seconds)
6.8	1.84	0.56
5.8	1.59	0.39
4.8	1.97	0.64
3.8	2.17	0.02
2.8	7.89	8.34

Table 6.13 Mean and standard deviations for the time it took block #1 to initially move away from the wall to the time it passed block #2.

As it can be seen, the deeper water depths had the quickest removal times. The large mean and standard deviation for the 2.8cm depth is due to the fact that one of the runs had block #1 initially move, but then it paused and was further sucked out seconds later. The importance of these times is that they are comparable to the stated research times for instantaneous velocity fluctuations, indicating that fluctuations above the mean velocity could be responsible for removal.

6.3.3 Sediment Removal

As the flow passed by the experimental wall during a run it was able to remove the sediment from in between the blocks and partially from behind the stones. Initially, the sediment in between the gaps was sucked out, which then lead to the sediment behind the block to start being removed. Depressions developed in the sediment where the sand was being sucked out through the gap. At the lowest point of the depression (at the edges of the armourstone) about 80% of the block was exposed, at the highest point (behind the middle of the stone) approximately 20% of the block was exposed. Each of the different sediment sizes used in this experiment reproduced similar depressions to those found behind the armourstone wall at Forty Mile Creek, which allowed the block to be surrounded by water.

6.3.4 Velocity against the Wall

The flow data collected by the ADV was analyzed to determine fluctuations within the flow. The mean velocities calculated for each depth were calculated by combining each run for a specific depth:

4.0cm depth = 62.35cm/sec
5.0cm depth = 84.37cm/sec
6.0cm depth = 78.94cm/sec
7.0cm depth = 68.99cm/sec

In order to analyze the flow data to determine whether there were periods of fast and slow moving water within the flow, the individual total velocities had to be compared to the overall mean. Figure 6.15 illustrates the fluctuation of velocity from the mean for a run with an initial depth of 4.0cm. This was achieved by subtracting the overall mean velocity from the individual point velocities. The figure shows a highlighted section where the point velocity is almost 80cm/sec above the mean flow velocity (see Figure 6.16 for detail). Figure 6.17 illustrates the amount of time velocity fluctuations are above the mean for the same run. This was done by assigning either a 1 if the point velocity was over the mean or a 0 if it was under the mean. For a period of 4.20 seconds during this run the flow velocity had an average of 83.82cm/sec, compared to a mean of 59.96cm/sec for the entire run.

Although only one probe was used in this data collection, analysis of the velocity measurements show that there are periods of faster moving water occurring in the flow profile, if they are high and long enough they could cause suction to occur.

6.3.5 Velocities in the Gaps

Three locations were chosen to collect velocity data behind block #1 and between block #1 and block #2. The first location is behind block #1 at the upstream corner, the second location is behind block #1 in the center, the third location is between block #1 and block #2 close to the channel flow (see Figure 6.18). The mean, standard deviation,

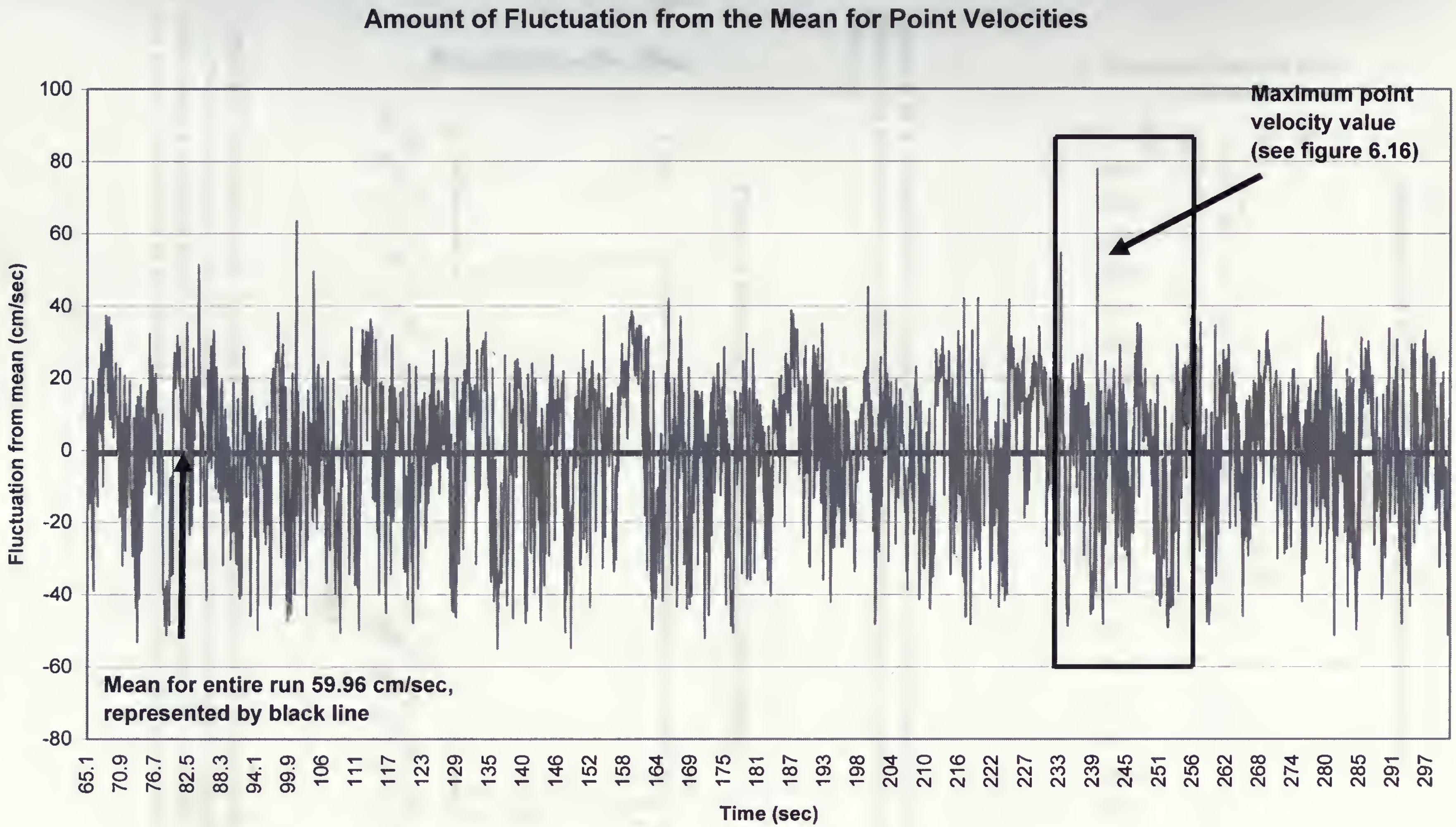

Figure 6.15 This graph shows the fluctuations of point velocities from the mean velocity for the entire experimental run, where the initial depth for this run was 4.0cm. It can be seen around 240 seconds (within the box) that velocity fluctuates from being below the mean to rising to almost 80 cm/sec above the mean.

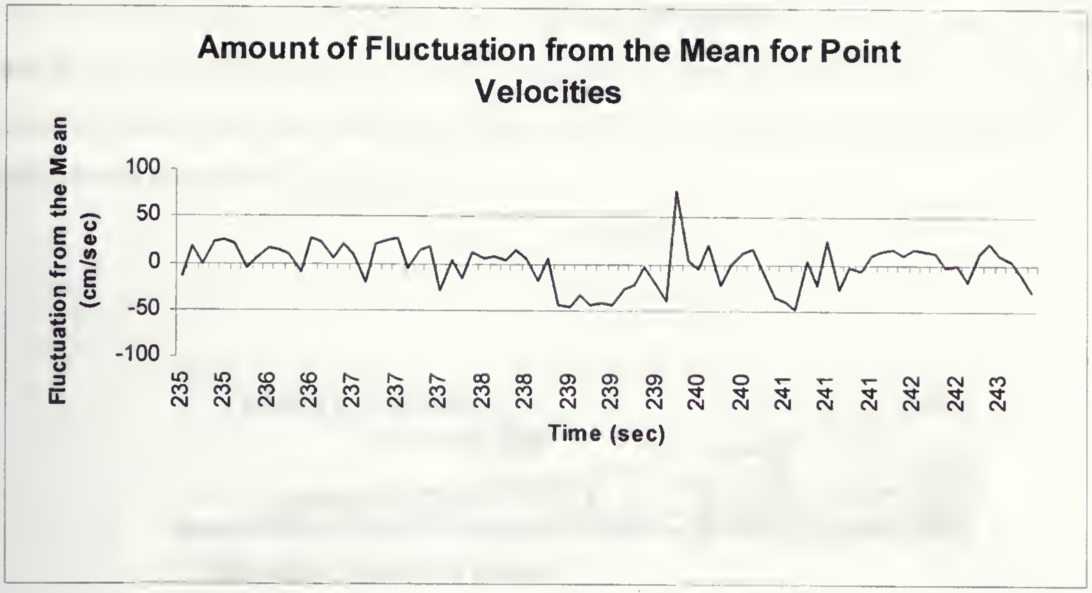

Figure 6.16 A detailed view of highlighted box in figure 6.15. It can be seen that around 238.65 seconds that velocity is below the mean, then at 239.85 seconds the velocity jumps to almost 80cm/sec above the mean.

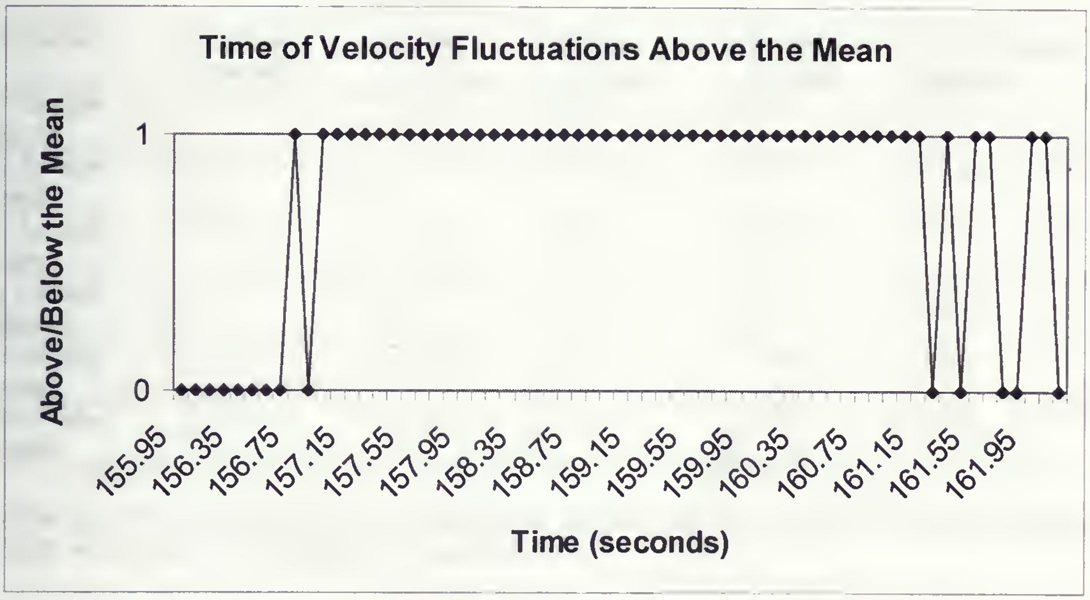

Figure 6.17 This graph shows the velocity fluctuations for the same run depicted in Figures 6.15 and 6.16. The total time for this run was 236 seconds (the first 65 seconds were not recorded by the probe due to low water depths as the pump speed increased) and the initial depth was 4.0cm. This period of 4.20 seconds had a mean flow velocity of 83.82cm/sec, compared to a mean of 59.96cm/sec for the entire run.

and total velocity for the X and Y flow are listed in Table 6.14. Looking downstream in the flume, a negative flow value is to the left for Y. The velocities collected in the gaps are much lower than the channel velocities, which would therefore result in the pressure differential needed for suction to occur.

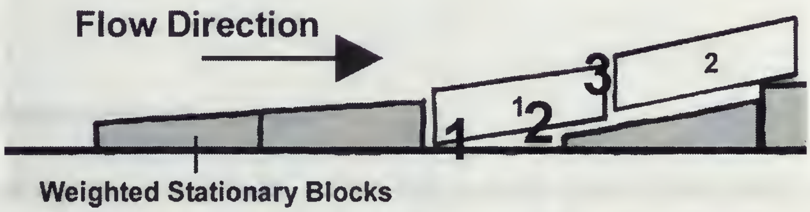

Figure 6.18 Locations chosen to collect velocity data behind and in between block #1 and block #2, represented by the larger bold numbers.

Location	X Mean (cm/sec)	X Std. (cm/sec)	Y Mean (cm/sec)	Y Std. (cm/sec)	Total Velocity (cm/sec)
1 for 4cm depth	30.31	1.57	-17.34	2.38	32.67
2 for 4cm depth	27.52	1.44	-14.89	2.39	31.36
3 for 4cm depth	19.18	1.25	-20.44	3.38	27.19
1 for 6cm depth	32.51	3.84	-14.00	3.11	33.82
2 for 6cm depth	21.23	2.66	-5.57	7.68	24.55
3 for 6cm depth	18.45	0.96	-13.45	4.34	22.82

Table 6.14 Flow velocities for locations behind and between block #1 and block #2 at the 4cm and 6cm depth, which are lower than the main channel velocities.

6.3.6 Corner Block

The corner block created to collect velocity data at the upstream end of block #1 provided velocity data by recording the maximum height of water within each tube and by using the velocity head formula.

$V = \sqrt{(2gH)}$ **Equation 6.1**

where *H* is the height of the water in the tube in meters.

Each of the velocity profiles can be seen in Figures 6.19 to 6.21, where each of the profiles shows a lower velocity at the bottom and increasing towards the top. Each of the velocities calculated for each tube are within the range of velocities collected from the ADV.

6.3.7 Other Velocity Measurements

The average surface velocity for the 4.8cm depth worked out to be 81cm/sec, which is an acceptable velocity measurement compared to the other velocity data collected.

For the three depths the wavelength of stationary waves remained fairly constant, this meant that the velocity for this area was consistent for the three depths. The velocity inferred from the wavelength was 83cm/sec, which is also a comparable velocity measurement from the surface and ADV data.

Since block #1 and block #4 were the only blocks that came away from the wall by themselves, scallop measurements were taken from these blocks. The formula used to calculate the mean was the Sauter Mean (White, 1988):

$\bar{L}_{32} = (\sum \ell^3_i / \sum \ell^2_i)2$ **Equation 6.2**

where $\bar{L}_{32}$ is the Sauter mean, ℓ_i is the lengths of individual scallops in a homogeneous population.

The scallop measurements were taken from the first 5 centimeters of the upstream end of block #1 and block #4, the Sauter mean worked out to be 0.87cm for block #1 and 1.08cm block #4. These lengths work out to give velocities over 300 cm/sec against the

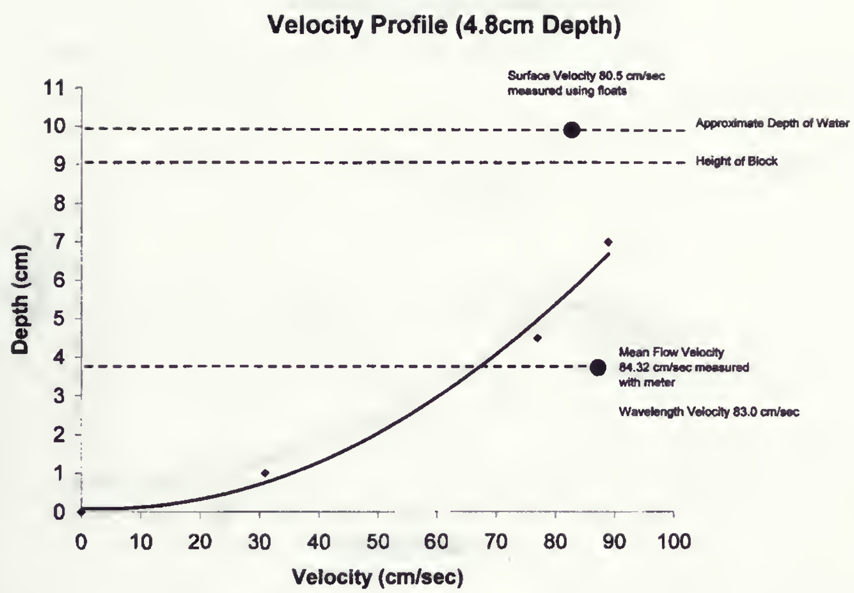

Figure 6.19 Velocity profile collected from the tube block at a static depth of 4.8cm. The velocities from the 3 tubes are plotted (represented by the diamond shapes). The mean flow velocity for the 4.8cm flow depth is plotted at the level of the mean velocity if the profile is logarithmic.

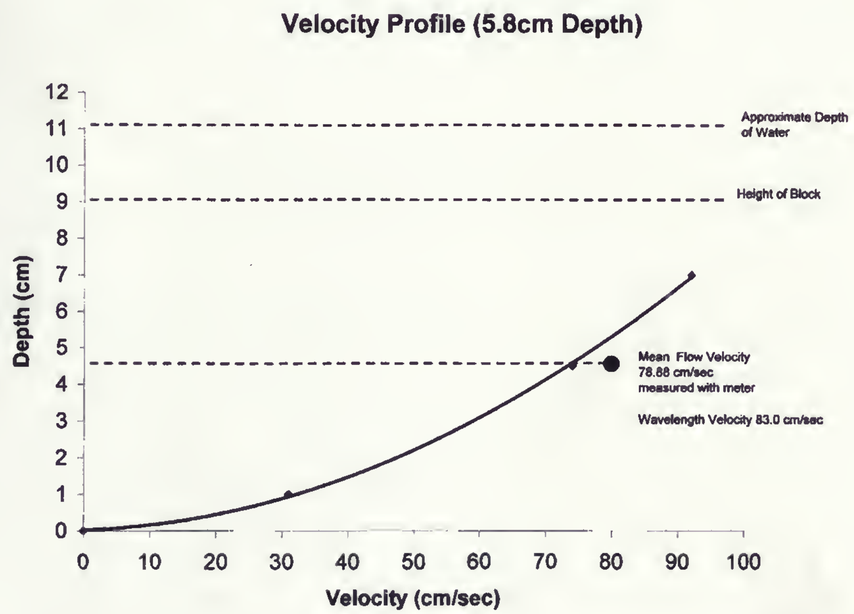

Figure 6.20 Velocity profile collected from the tube block at a static depth of 5.8cm. The velocities from the 3 tubes are plotted (represented by the diamond shapes). The mean flow velocity for the 5.8cm flow depth is plotted at the level of the mean velocity if the profile is logarithmic.

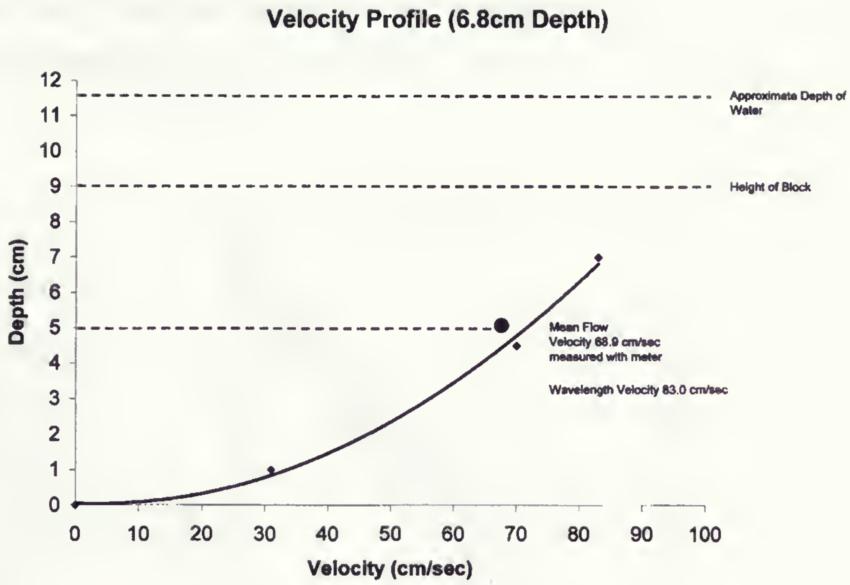

Figure 6.21 Velocity profile collected from the tube block at a static depth of 6.8cm. The velocities from the 3 tubes are plotted (represented by the diamond shapes). The mean flow velocity for the 6.8cm flow depth is plotted at the level of the mean velocity if the profile is logarithmic.

experimental wall. Although this method provided velocity data, the results were much higher than expected (see Figure 6.22) and are probably not reliable.

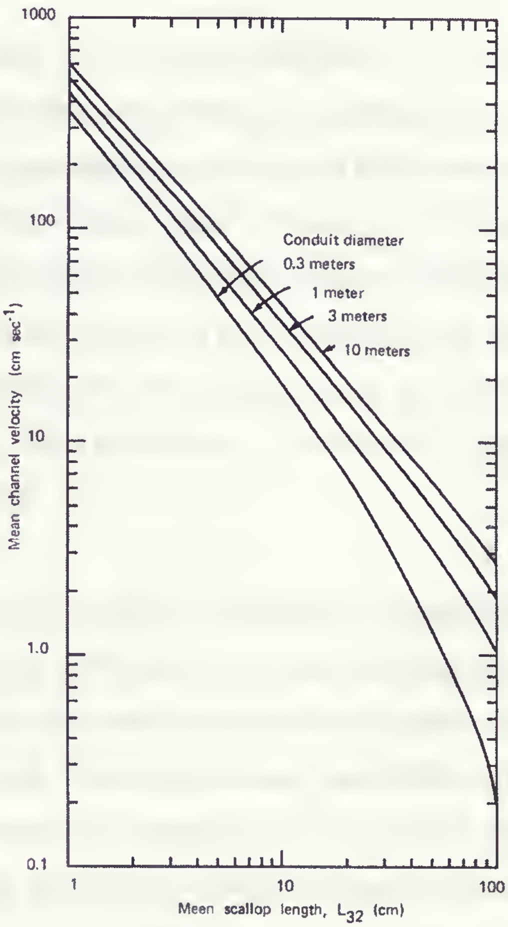

Figure 6.22 Diagram showing the relationship between mean scallop length and velocity. Velocity can be determined from this diagram once mean scallop length is known, taken from White, 1988.

Chapter 7 – Discussion

The structural failure of the armourstone wall at Forty Mile Creek in Grimsby is different than other armourstone wall failures seen during fieldwork. This was due to the fact that toe scour is not responsible for the removal of the two stones. The theoretical basis for the removal of these stones is due to the process of lateral suction, which has previously not been considered as a failure mechanism. The hydraulic and physical variables that contribute to the process of suction, which work in a similar manner as the process of quarrying, makes prediction challenging but fieldwork and experimental work indicate their importance. How the process of suction can be applied to the armourstone wall will be discussed below.

Velocity is the most significant component for the suction removal of armourstone blocks because as the velocity increases so does the flow force exerted. Large scale velocity fluctuations which deviate from the mean velocity for a specific amount of time are known to exist in both natural and artificial channels. These fluctuations would also increase in magnitude as the velocities rise. Buffin-Belanger *et al.* (2000) found that these fast and slow wedges of water lasted for a mean duration of 2 seconds. Kirkbride and Ferguson (1995) also found that higher and lower than average velocities occurred within the water profile and lasted for up to 3 seconds.

Analysis of flow data collected during the flume experiment for this project also shows that velocity fluctuates about the mean. Durations of approximately 2.0 to 6.0 seconds produced mean velocities that ranged from 6.0 to 33.0cm/sec higher than the mean flow velocity. An example of this was shown in Figure 6.17 where the average velocity for the entire experimental run was 59.96cm/sec, but for a period of 4.20 seconds the mean was 83.82cm/sec.

The conditions of layout, depth, and pump speed during the experimental work seemed to remain constant visually, but block removal remained unpredictable. From the onset of movement for block #1 to it being carried downstream by the flow took less than 2 seconds for the deeper water depths, which suggests that momentary increases in velocity have occurred. Experimentally, block removal was relatively quick and therefore a large deviation of velocity from its mean could be substantial enough to provide the flow force needed to cause suction.

Surface velocities measured in the field at Forty Mile Creek not only show that the mean velocity along the selected streamline can get higher than that calculated by hydraulic programs, as was seen when compared to flow data from HEC RAS and the floodplain analysis (Table 5.1), but also that critical flow exists in this section, indicating the stream is at its maximum efficiency. Hydraulic programs determine the mean velocity within the water profile, but evidence shows that at a given point in the flow, especially along a steep wall, localized and short-term velocity fluctuations can be substantially higher.

The design of the armourstone wall allows these high flow velocities to contribute to suction removal of the blocks. The process of suction is caused by a difference in pressure due to velocity and for a pressure difference to be effective there must be water surrounding the stone within the wall.

Fieldwork has shown that the armourstone blocks are of variable shapes and sizes, which leads to the presence of gaps in between the stones when they are placed on top and beside one another. This obviously is a known problem because grout and riprap have been used to reduce the sizes of these gaps, although the use of riprap would not be beneficial since ultimately high flow velocities will remove these small pieces of stone

away from the wall. The removal of loose sediment initially placed during construction behind the top layer of blocks in the wall has been identified during fieldwork by the presence of depressions behind the block and this process was also reproduced in the flume. The removal of sediment by suction was also identified by Sumer et al. (2001) when sediment was removed from between blocks placed along the bed weakening the structural integrity. It is the presence of these gaps and depressions in behind the top stone that allow the water to completely surround the stone. When the discharge in the stream is high enough there will be slow moving water in behind the stone and fast moving water in front of the stone, thus creating the pressure differential. The difference in velocities on either side of the block was also recreated in the flume.

The primary forces that contribute to the resistance of the block are the buoyant weight and the friction. The buoyant weight of the block is controlled by how much of the block is submerged with water, the more submerged it is (up to total submergence) the greater the buoyancy, therefore the easier it is removed. This relationship was reproduced during the flume experiment where the deeper water flow had the most blocks removed. Friction influences the blocks resistance to movement and the variability of surface roughness and even the use of grout would have an effect on the friction value. Since this variable is difficult to determine accurately, the spreadsheet created can be used to test different values, so that although an exact value for friction cannot be made, a rough estimate is possible.

Reinus (1986) found in his experimental work for bed quarrying that a protrusion into the flow influenced the process of suction and planimetric offset is suggested for the design of armourstone walls by the Maryland Guidelines (2000). Experimental work for this project showed that offset into the flow did not seem to influence whether the block was removed or not. The blocks in the flume experiment were removed with either a 2mm offset or with no offset.

All the armourstone walls studied during fieldwork had the rocks placed so that the long axis was parallel to the stream channel, which seems to be done due to the cost of the individual stones. When the average long axis lengths were measured during fieldwork some of the walls had shorter lengths along the top layer of the wall. Although only the one axis was measured, this may indicate that smaller blocks are used along the top of the wall. Since surface velocities are faster than the rest of the flow, the top layer stones would be more likely to be removed, therefore larger stones should be used.

When the stability ratio (Equation 4.5) is used, the only direction that is significant for suction to occur is the length of the block perpendicular to the exerted flow, which in armourstone design is often the shortest block dimension. The way in which the rocks are placed within the wall provides ideal conditions for suction to remove the rocks because the gaps that are produced by uneven rock surfaces and the sediment removal allow water to surround the stone and increase its buoyancy, therefore reducing the rock resistance. If the rocks were rotated, so that the longest length of the block was perpendicular to the stream channel, larger flow velocities would be needed to remove them. This will be further explored in the following section.

Using the spreadsheet that was created to determine threshold velocities, the velocities needed to remove the stone from the wall at Forty Mile Creek can be calculated. Tables 7.1 and 7.2 show the different threshold velocities by altering the friction and the length of y for the stone. Table 7.1 shows velocities for a density of 2500kg/m3 and Table 7.2 shows the velocities for a density of 2600kg/m3. By looking at the two tables it can be seen that slight increases in friction and length of y will increase velocity slightly, but significant increases in the length of y will require much larger flow velocities to remove the stone (refer to Figure 4.1).

Threshold Velocity Density 2500 kg/m^3			
Friction / Y Length	0.55	0.75	1.0
0.65m	3.25m/sec	3.8m/sec	4.4m/sec
0.75m	3.5m/sec	4.1m/sec	4.7m/sec
0.85m	3.75m/sec	4.35m/sec	5.1m/sec
0.95m	3.95m/sec	4.6m/sec	5.3m/sec
1.30m	4.6m/sec	5.4m/sec	6.2m/sec

Table 7.1 Sensitivity Analysis – Threshold velocities for movement of armourstone block by suction, using a density of 2500kg/m3 and altering the friction and length of y.

Threshold Velocity Density 2600 kg/m^3			
Friction / Y Length	0.55	0.75	1.0
0.65m	3.4m/sec	3.95m/sec	4.55m/sec
0.75m	3.6m/sec	4.25m/sec	4.9m/sec
0.85m	3.85m/sec	4.5m/sec	5.2m/sec
0.95m	4.05m/sec	4.75m/sec	5.5m/sec
1.30m	4.8m/sec	5.6m/sec	6.4m/sec

Table 7.2 Sensitivity Analysis – Threshold velocities for movement of armourstone block by suction, using a density of 2600kg/m3 and altering friction and length of y.

The values in Tables 7.1 and 7.2 are reasonable velocities that could occur at Forty Mile Creek, specifically the velocities below 5.0m/sec. Although mean velocities calculated by the hydraulic programs are not as high, the highest surface velocity measured during fieldwork was 3.19m/sec and this was not at bankfull discharge. Larger discharges will produce higher mean velocities as well as higher surface velocities. Fluctuations from the mean will also cause momentary increases in velocity that could be high enough to remove the stones.

Field and experimental work have lead to the conclusion that suction is the process that is responsible for removing the two stones out of the armourstone wall at Forty Mile Creek. The placement of stones within this wall produces large gaps that

allow water to get in between them as well as behind them, which was seen during periods of high discharges. Although bankfull discharges were not seen at Forty Mile Creek during field research, the presence of depressions behind the top layer of stone due to the removal of sediment would indicate that they have occurred, although full submergence of the armourstone is not necessary for sediment removal or removal by suction. Overnight on April 4, 2005 trash lines show that bankfull discharge occurred along this section of Forty Mile Creek and this led to the removal of riprap from between the armourstones. Surface velocities measured in the field show that the flow can get much higher than the average velocities computed by hydraulic programs, which would also indicate that velocity fluctuations could be higher. Since the stones were placed on top of one another and not in the 'brick wall' design mentioned in the Maryland Guidelines (2000), evidence suggests that high surface velocities 'sucked' out the top stone first, which left the bottom stone vulnerable because the additional top weight was removed.

Toe scour was eliminated as a cause of failure at Forty Mile Creek because the footer stones were still intact and they were not removed and replaced during the restoration process. Walls that are primarily influenced by toe scour would still have suction impact the removal of stones from the wall. This is due to the increased angle of the stone as it leans toward the stream channel, which would lower the rock resistance (Equation 4.3) for the stability ratio (Equation 4.5). Therefore, the process of suction could be a contributory cause of failure for the wall. As long as armourstone walls are designed and built similar to the wall at Forty Mile Creek, suction can be considered as a method of failure.

Chapter 8 – Conclusion

Streambank restoration is designed to prevent erosion of the surrounding land and it is based on the hydraulic and physical characteristics of the stream. Armourstone walls are built because they provide structural support and have a 'natural' appearance due to the use of local rock. It was determined that the only apparent cause of failure for the armourstone wall at Forty Mile Creek in Grimsby was due to the process of suction. This was based on physical and hydraulic evidence found in the field and studied in the flume.

The mechanism of suction has not been taken into consideration when designing bank stabilization structures and the only applied theory of suction is limited to the research on quarrying, which removes large blocks of stone off the bed. Lateral suction is believed to work in a similar way as the process of quarrying and can impact the stability of a structure. This thesis has illustrated how suction can specifically impact armourstone revetments, but ultimately all structures will be impacted by suction. Some examples include: the removal of fractured pieces from cement walls; the removal of riprap from broken gabion baskets; and even natural rock faces along a streambank can be impacted by suction. Research indicates that if sufficient velocities are obtained then suction will occur, but fluctuations of velocity and other variables involved in the movement are not easy to measure and for this reason prediction is difficult. Experimentally, these variables can be explored to determine their significance. Since suction is a force that is known to occur within the stream and although prediction is difficult, adjustments should be made to the structure to limit the effect.

Recommendations

1. Adaptations to combat the problem of large gaps between the stones include the placement of riprap and grout in the gaps, as well as planting vegetation at the top of the bank. This is done to limit the amount of water that can surround the stones, as well as to stop water from eroding the sediment in

behind the top block. Over time preventative maintenance should be done to ensure that these solutions are still providing structural support.

2. The blocks of rock should be tight fitting, so that the gaps between the rocks are kept small, which will lessen the possibility of the rocks moving away from the wall. The rocks should also be placed so that there is more interlocking between the rocks, therefore increasing the role of friction in suction removal.

3. Since surface velocities are faster than the rest of the flow, smaller blocks placed along the top layer of the wall should be avoided due to the greater chance of them being removed by suction. The size of the block used should be based on the threshold velocity for a given stream.

4. Identify possible locations for critical flow (Froude ≈ 1) along the stream so that the location of high velocities are known, therefore preventative measures can be taken to limit the effect of suction. Threshold velocities for suction should be determined at these locations and velocities used for design purposes should not be based on averages.

5. The armourstones should be rotated so that the long axis of the stone is perpendicular to the stream channel instead of being parallel. Since it is the perpendicular length of the stone that influences the stability ratio (equation 4.5) this would increase the rock resistance, therefore requiring higher flow velocities to remove it from the wall. Since it would be a greater expense to build the whole wall in this manner, it may be enough to build the wall this way in areas where velocities are estimated to be near the threshold for suction. Such areas may include: locations with steep bank slopes where the flow is directed along it; locations where the elevation of the streambed significantly changes; along the outer bank of stream bends; and where the channel becomes constricted.

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Assessment of Rock Stability

Comments	Required Properties	Quantities	Units	
	Flow Properties			
Depth of flow	FlowTop	0.75	m	
	FlowMass	1000	kg/m^3	
	FlowVelocity	4.500	m/s	
	FlowForce Exerted	11188.125	Newtons kg m/s^2	
	Rock Properties			
Set to z	RockTop	0.85	m	
Vertical	z	0.85	m	
Across flow (perpendicular to flow)	y	0.75	m	
Along flow (parallel to flow)	x	1.30	m	
	RockMass	2500	kg/m^3	
No friction, no submergence	Rock Resistance	20325.09	Newtons kg m/s^2	
	Rock Resistance in Water	13151.53	Newtons kg m/s^2	
	Other Constants and Properties			
	Gravity	9.81	m/s^2	
Determined by experiment	Friction	0.7	Dimensionless	
Equal to 1	Suction Coefficient	1.00	Dimensionless	
	Derived Quantities			
If flow depth exceeds block height	Total Submerged Mass	1500	kg/m^3	
Computes based on proportion	Partial Submergence Mass	1617.647059	kg/m^3	
	Proportion Submerged	0.88	Dimensionless	
	Outcome			
From above	FlowForce Exerted	11188.125	Newtons	
Newtons to spare if positive		1982.05	Newtons	
Ratio of force to resistance	FlowForce Exerted/Rock Resistance	1.215	Dimensionless	
Newtons lacking if negative		-1982.05	Newtons	
adds in the friction ...	Rock Resistance in water * Friction	9206.07	Newtons	
Depth of channel for critical velocity	Depth for critical (threshold) velocity	2.06		
	Reynolds Number	7090832.69	Dimensionless	Turbulent
	Froude Number	1.00	Dimensionless	Near Critical Flow

Example of spreadsheet created for lateral suction

Program to compute flow statistics from floats

Enter your float times in column 1 & length of reach used for timings
everything is automatic - including the "n" count (cell E9)

- HOWEVER - enter gauge and/or streamline depth in cm to get Froude # with error range based on velocity data

- If you enter values for reach slope and streamline depth
the program will estimate mean velocity on the basis of a logarithmic flow profile, and provide shear velocity and related data

Field Book reference	
date:	*11/28/2003 - 10:30am*
River	*Forty Mile Creek*
Reach	*Coronation Park*

list#	*data*	*stats*					**- 2 se**	*in cm*	**+ 2 se**	
1	8.12	**mean**	number>>	9		**Gauge >>**		17.5		*if available*
2	8.71	7.43	reach dist>	10	<< metres	**Depth >>**		17.5		*along streamline*
3	6.86	**st dev**	**mean vel >**	1.35		**Est Froude #**	0.94	1.03	1.13	**gauge**
4	6.52	1.05	min vel >	1.04	< max time	**st Froude #**	0.94	1.03	1.13	**streamline**
5	6.89	**st error**	max vel >	1.53	< min time					
6	7.23	0.350	se min vel >	1.23	<< +/- 2					
7	7.08		se mx vel >	1.49	<< +/- 2	Reach slop	0.014	0.96	**<< mean velocity of sampled flow**	
8	9.64		sd min vel >	1.05	<< +/- 2					
9	7.30		sd max vel >	1.88	<< +/- 2	**hear velocit**	1.02	*m/s*		
10	6.62					**shear stres**	24.03	*N/m^2*		
11						**power**	23.04	*W/m^2*		
12										
13										
14										
15										
16										
17										
18										
19										
20										

Program to compute flow statistics from floats

Enter your float times in column 1 & length of reach used for timings
everything is automatic - including the "n" count (cell E9)

- HOWEVER - enter gauge and/or streamline depth in cm to get Froude # with error range based on velocity data

- If you enter values for reach slope and streamline depth
the program will estimate mean velocity on the basis of a logarithmic flow profile, and provide shear velocity and related data

Field Book reference	
date:	*11/28/2003 - 4:50pm*
River	*Forty Mile Creek*
Reach	*Coronation Park*

list#	*data*	*stats*					**- 2 se**	***in cm***	**+ 2 se**	
1	5.03	**mean**	number>>	7		**Gauge >>**		36.25		*if available*
2	4.86	4.73	reach dist>	10	<< metres	**Depth >>**		36.25		*along streamline*
3	4.98	**st dev**	**mean vel >**	2.12		**Est Froude #**	1.09	1.12	1.16	**gauge**
4	4.62	0.20	min vel >	2.01	< max time	**Est Froude #**	1.09	1.12	1.16	**streamline**
5	4.68	**st error**	max vel >	2.28	< min time					
6	4.89	0.075	se min vel >	2.05	<< +/- 2					
7	4.39		se mx vel >	2.19	<< +/- 2	**Reach slope**	0.014	1.56	<u>**<< mean velocity of sampled flow**</u>	
8	4.67		sd min vel >	1.95	<< +/- 2					
9			sd max vel >	2.31	<< +/- 2	**shear velocity**	1.02	*m/s*		
10						**shear stress**	49.79	*N/m^2*		
11						**power**	77.55	*W/m^2*		
12										
13										
14										
15										
16										
17										
18										
19										
20										

Program to compute flow statistics from floats

Enter your float times in column 1 & length of reach used for timings
everything is automatic - including the "n" count (cell E9)

- HOWEVER - enter gauge and/or streamline depth in cm to get Froude # with error range based on velocity data

- If you enter values for reach slope and streamline depth
the program will estimate mean velocity on the basis of a logarithmic flow profile, and provide shear velocity and related data

Field Book referenc	
date:	*11/29/2003 - 10:30am*
River	*Forty Mile Creek*
Reach	*Coronation Park*

list#	*data*	*stats*					**- 2 se**	*in cm*	**+ 2 se**	
1	7.80	**mean**	number>>	11		**Gauge >>**		36.25		*if available*
2	4.37	5.07	reach dist>	10	<< metres	**Depth >>**		36.25		*along streamline*
3	4.75	**st dev**	mean vel >	1.97		**Est Froude #**	0.92	1.04	1.21	**gauge**
4	4.28	1.17	min vel >	1.28	< max time	**Est Froude #**	0.92	1.04	1.21	**streamline**
5	4.42	**st error**	max vel >	2.34	< min time					
6	4.46	0.352	se min vel >	1.73	<< +/- 2					
7	4.58		se mx vel >	2.29	<< +/- 2	**Reach slope**	0.014	1.41		<ins><< mean velocity of sampled flow</ins>
8	4.86		sd min vel >	1.35	<< +/- 2					
9	5.15		sd max vel >	3.65	<< +/- 2	**shear velocity**	1.02	*m/s*		
10	4.28					**shear stress**	49.79	*N/m^2*		
11	6.87					**power**	70.34	*W/m^2*		
12										
13										
14										
15										
16										
17										
18										
19										
20										

Program to compute flow statistics from floats

Enter your float times in column 1 & length of reach used for timings
everything is automatic - including the "n" count (cell E9)

- HOWEVER - enter gauge and/or streamline depth in cm to get Froude # with error range based on velocity data

- If you enter values for reach slope and streamline depth
the program will estimate mean velocity on the basis of a logarithmic flow profile, and provide shear velocity and related data

Field Book reference	
date:	*12/24/2003 - 11:30am*
River	*Forty Mile Creek*
Reach	*Coronation Park*

list#	*data*	*stats*					**- 2 se**	***in cm***	**+ 2 se**	
1	4.43	**mean**	number>>	12		**Gauge >>**		20		*if available*
2	4.12	3.77	reach dist>	6	<< metres	**Depth >>**		20		*along streamline*
3	4.90	**st dev**	**mean vel >**	1.59		**Est Froude #**	1.05	1.14	1.25	**gauge**
4	3.43	0.57	min vel >	1.22	< max time	**st Froude #**	1.05	1.14	1.25	**streamline**
5	3.27	**st error**	max vel >	2.08	< min time					
6	4.12	0.164	se min vel >	1.46	<< +/- 2					
7	3.68		se mx vel >	1.74	<< +/- 2	**Reach slop**	0.014	1.18	**<< mean velocity of sampled flow**	
8	3.52		sd min vel >	1.22	<< +/- 2					
9	3.93		sd max vel >	2.28	<< +/- 2	**hear velocit**	1.02	*m/s*		
10	4.28					**shear stres**	27.47	*N/m^2*		
11	3.30					**power**	32.37	*W/m^2*		
12	2.89									
13										
14										
15										
16										
17										
18										
19										
20										

Program to compute flow statistics from floats

-> Enter your float times in column 1 & length of reach used for timings
everything is automatic for velocity calculations - including the "n" count (cell E21)

-> Enter gauge and/or streamline depth in cm to get Froude # with error range based on velocity data

-> If you enter values for reach slope and streamline depth
the program will estimate mean velocity on the basis of a logarithmic flow profile, and provide shear velocity and relate

Field Book referenc	
date:	*3/2/2004 9:30am*
River	*40 Mile Creek (ON)*
Reach	*Coronation Park*

list#	*data*	*data stats*										
							- 2 se	***in cm***	**+ 2 se**			
1	4.61	**mean**	number>>	10		**Gauge >>**		50.8		*if available*		
2	5.02	4.86	reach dist>	10	<< metres	**Depth >>**		50.8		*along streamline*	gravity	9.81
3	5.98	**st dev**	**mean surf vel >**	2.06		**(Est Froude #**	0.55	0.63	0.71	**gauge - if relevant)**		
4	5.10	0.67	min vel >	1.67	< max time	**Est Froude #**	0.55	0.63	0.71	**streamline**		
5	5.48	**st error**	max vel >	2.60	< min time							
6	4.77	0.212	se min vel >	1.89	<< +/- 2							
7	3.84		se mx vel >	2.25	<< +/- 2	**Reach slope**	0.014	1.40	**<< mean velocity of sampled flow**			
8	5.30		sd min vel >	1.61	<< +/- 2							
9	3.89		sd max vel >	2.84	<< +/- 2	**shear velocity**	0.66	*m/s*				
10	4.61					**shear stress**	70	*N/m^2*				
11						**power**	97	*W/m^2*				
12						**largest bed particle**	96	*mm*				
13												
14												
15												
16												
17												
18												
19												
20												

Program to compute flow statistics from floats

-> Enter your float times in column 1 & length of reach used for timings
everything is automatic for velocity calculations - including the "n" count (cell E21)

-> Enter gauge and/or streamline depth in cm to get Froude # with error range based on velocity data

-> If you enter values for reach slope and streamline depth
the program will estimate mean velocity on the basis of a logarithmic flow profile, and provide shear velocity and relate

Field Book referenc	
date:	*3/2/2004 5:30pm*
River	*40 Mile Creek (ON)*
Reach	*Coronation Park*

list#	*data*	*data stats*					**- 2 se**	***in cm***	**+ 2 se**			
1	5.55	**mean**	number>>	10		**Gauge >>**		66.04		*if available*		
2	3.15	3.14	reach dist>	10	<< metres	**Depth >>**		66.04		*along streamline*	gravity	9.81
3	2.95	**st dev**	**mean surf vel >**	3.19		**(Est Froude #**	0.76	0.96	1.24	**gauge - if relevant)**		
4	2.34	0.92	min vel >	1.80	< max time	**Est Froude #**	0.76	0.96	1.24	**streamline**		
5	2.42	**st error**	max vel >	4.27	< min time							
6	2.80	0.289	se min vel >	2.69	<< +/- 2							
7	2.59		se mx vel >	3.91	<< +/- 2	**Reach slope**	0.014	2.44	**<< mean velocity of sampled flow**			
8	3.08		sd min vel >	2.01	<< +/- 2							
9	3.02		sd max vel >	7.66	<< +/- 2	**shear velocity**	0.75	*m/s*				
10	3.46					**shear stress**	91	*N/m^2*				
11						**power**	221	*W/m^2*				
12						**largest bed particle**	124	*mm*				
13												
14												
15												
16												
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Program to compute flow statistics from floats

-> Enter your float times in column 1 & length of reach used for timings
everything is automatic for velocity calculations - including the "n" count (cell E21)

-> Enter gauge and/or streamline depth in cm to get Froude # with error range based on velocity data

-> If you enter values for reach slope and streamline depth
the program will estimate mean velocity on the basis of a logarithmic flow profile, and provide shear velocity and relate

Field Book referenc	
date:	*March 5 2004*
River	*40 Mile Creek (ON)*
Reach	*Coronation Park*

list#	*data*	*data stats*										
							- 2 se	*in cm*	**+ 2 se**			
1	3.96	**mean**	number>>	12		**Gauge >>**		50.8		*if available*		
2	3.03	3.13	reach dist>	10	<< metres	**Depth >>**		50.8		*along streamline*	gravity	9.81
3	2.70	**st dev**	**mean surf vel >**	3.19		**(Est Froude #**	1.04	1.13	1.25	**gauge - if relevant)**		
4	2.80	0.40	min vel >	2.53	< max time	**Est Froude #**	1.04	1.13	1.25	**streamline**		
5	2.71	**st error**	max vel >	3.73	< min time							
6	3.28	0.115	se min vel >	2.97	<< +/- 2							
7	3.20		se mx vel >	3.44	<< +/- 2	**Reach slope**	0.014	2.53	<u><< mean velocity of sampled flow</u>			
8	3.70		sd min vel >	2.55	<< +/- 2							
9	3.21		sd max vel >	4.28	<< +/- 2	**shear velocity**	0.66	*m/s*				
10	2.68					**shear stress**	70	*N/m^2*				
11	3.15					**power**	177	*W/m^2*				
12	3.17					**largest bed particle**	96	*mm*				
13												
14												
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Program to compute flow statistics from floats

-> Enter your float times in column 1 & length of reach used for timings
everything is automatic for velocity calculations - including the "n" count (cell E21)

-> Enter gauge and/or streamline depth in cm to get Froude # with error range based on velocity data

-> If you enter values for reach slope and streamline depth
the program will estimate mean velocity on the basis of a logarithmic flow profile, and provide shear velocity and relate

Field Book referenc	
date:	*April 14 2004*
River	*40 Mile Creek (ON)*
Reach	*Coronation Park*

list#	*data*	*data stats*											
							- 2 se	***in cm***	**+ 2 se**				
1	3.95	**mean**	number>>	10		**Gauge >>**		38.1		*if available*			
2	3.78	3.96	reach dist>	10	<< metres	**Depth >>**		38.1		*along streamline*	gravity	9.81	
3	4.33	**st dev**	**mean surf vel >**	2.52		**(Est Froude #**	0.96	1.01	1.06	**gauge - if relevant)**			
4	3.78	0.24	min vel >	2.31	< max time	**Est Froude #**	0.96	1.01	1.06	**streamline**			
5	4.20	**st error**	max vel >	2.77	< min time								
6	4.09	0.076	se min vel >	2.43	<< +/- 2								
7	3.71		se mx vel >	2.62	<< +/- 2	**Reach slope**	0.014	1.95	**<< mean velocity of sampled flow**				
8	4.20		sd min vel >	2.25	<< +/- 2								
9	3.61		sd max vel >	2.87	<< +/- 2	**shear velocity**	0.57	*m/s*					
10	3.98					**shear stress**	52	*N/m^2*					
11						**power**	102	*W/m^2*					
12						**largest bed particle**	72	*mm*					
13													
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Program to compute flow statistics from floats

-> Enter your float times in column 1 & length of reach used for timings
everything is automatic for velocity calculations - including the "n" count (cell E21)

-> Enter gauge and/or streamline depth in cm to get Froude # with error range based on velocity data

-> If you enter values for reach slope and streamline depth
the program will estimate mean velocity on the basis of a logarithmic flow profile, and provide shear velocity and relate

Field Book referenc	
date:	*May 24 2004*
River	*40 Mile Creek (ON)*
Reach	*Coronation Park*

list#	*data*	*data stats*					**- 2 se**	***in cm***	**+ 2 se**			
1	5.42	**mean**	number>>	10		**Gauge >>**		38.1		*if available*		
2	4.68	4.79	reach dist>	10	<< metres	**Depth >>**		38.1		*along streamline*	gravity	9.81
3	4.78	**st dev**	**mean surf vel >**	2.09		**(Est Froude #**	0.75	0.80	0.85	**gauge - if relevant)**		
4	4.68	0.36	min vel >	1.85	< max time	**Est Froude #**	0.75	0.80	0.85	**streamline**		
5	4.78	**st error**	max vel >	2.35	< min time							
6	5.11	0.115	se min vel >	1.99	<< +/- 2							
7	4.37		se mx vel >	2.19	<< +/- 2	**Reach slope**	0.014	1.54	**<< mean velocity of sampled flow**			
8	4.25		sd min vel >	1.81	<< +/- 2							
9	4.61		sd max vel >	2.46	<< +/- 2	**shear velocity**	0.55	*m/s*				
10	5.20					**shear stress**	52	*N/m^2*				
11						**power**	81	*W/m^2*				
12						**largest bed particle**	72	*mm*				
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