Hydraulic Model Study:

Incipient motion tests on the Bosun Buffalo erosion protection blocks

Final Report rev01

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Submitted to:
The Bosun Group
PO Box 7313
Halfway House
Midrand, 1685
South Africa

Submitted by:
Stellenbosch University
Private Bag X1
Matieland, 7602
Stellenbosch
South Africa

Table of Contents

LIST OF FIGURES

LIST OF TABLES

1. Introduction

The Bosun Group approached Stellenbosch University (SU) during October 2021 to do a 1:3 scale physical model study of the hydraulic stability of the Bosun Buffalo erosion protection blocks (Figure 1-1), at the Hydraulics Laboratory, Department of Civil Engineering of Stellenbosch University.

The required key outcomes of the study were:

- To investigate the hydraulic stability of the Buffalo blocks;
- To compare the incipient motion condition of the Buffalo blocks with other typical erosion protection measures such as riprap (dumped rock) and Armorflex;
- To provide key hydraulic design guidelines for the Buffalo blocks, including Excel based calculations as a simplified hydraulic design guideline for the blocks.

Figure 1-1: Bosun model blocks at scale of 1:3

2. Background

2.1. Movability number to describe incipient motion

Investigating the hydraulic stability of the Buffalo blocks requires the determination of the flow conditions under which at least one block loses contact with the foundation bed and is lifted out of plane under hydraulic flow – a term coined as incipient motion or the threshold of movement or block failure. This concept is demonstrated in Figure 2-1.

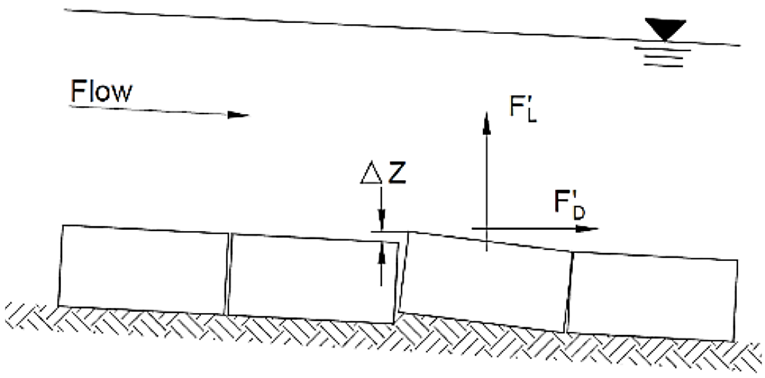

Figure 2-1: Schematic defining block failure at the threshold of movement

The three most common approaches to incipient motion are critical flow velocity, Shields' critical shear stress and Lui's stream power, of which the latter was used in this study. Defining a critical flow velocity for particle movement is considered insufficient because although flow velocity is easy to determine, it does not represent the velocity in the vicinity of the particle under consideration. The shear stress theory defines incipient motion as the limit at which the drag force exerted on a particle exceeds the resistive force. However, the theory only considers tangential forces and not vertical lift forces. Furthermore, Rooseboom (1992) suggested that the median particle size is not a sufficient parameter to adequately describe incipient motion and that settling velocity should rather be used. Liu instead used the stream-power theory to develop the movability number as a function of the particle Reynolds number. The movability number and the particle Reynolds number (Re_p or Re^*) are defined in Equations 1 and 2 respectively.

$$\frac{v^*}{w} = \frac{\sqrt{gyS_f}}{w} \tag{1}$$

$$Re_p = \frac{v^* d}{\nu} = \frac{\sqrt{gyS_f}d}{\nu} \tag{2}$$

Where:

v^* = shear velocity (m/s)
S_f = energy slope (m/m)
g = gravitational acceleration (9.81 m/s^2)
ν = kinematic viscosity of water at 15°C (1.13 x 10^{-6} m/s)
w = settling velocity (m/s)
y = flow depth (m)
d = particle diameter (m)
Re_p = particle Reynolds Number

Many researchers have proposed Movability Numbers for laminar and turbulent flow conditions, as presented graphically in Figure 2-2. The graph is easy to understand in that, if it plots above a specific Movability Number, movement will commence. For turbulent flow conditions, in the vicinity of the particle, particle settling velocity is constant. By assuming that the flow is uniform and homogeneous, many researchers showed that the Movability Number plots along a horizontal line for a certain flow condition and particle size (Langmaak 2013), as shown in Figure 2-2. Even though Shields and Liu assume uniform flow, researchers such as Yang (1973), Rooseboom (1992), Przedwojski et al (1995), Stoffberg (2005) and Langmaak (2013) support Liu's (1957) stream-power model for providing the soundest theoretical base of incipient motion theory for noncohesive particles in natural rivers. For prefabricated paving blocks the South African National Roads Agency Limited (SANRAL 2013) recommends a Movability Number of 0.12 at particle Reynolds Numbers larger than 13.

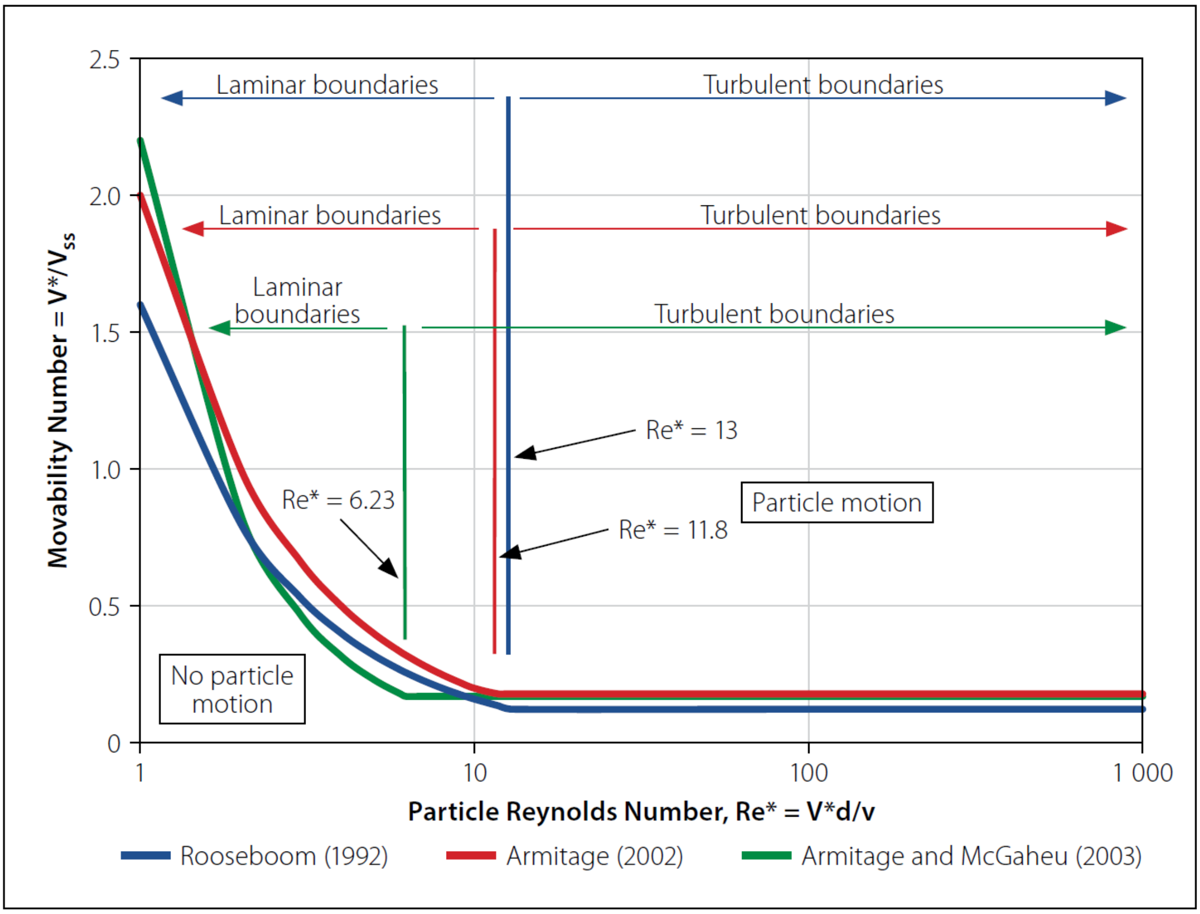

Figure 2-2: Incipient motion criteria of Rooseboom (1992), Armitage (2002), Armitage and McGahey (2003)

It should be noted that only incipient motion as a result of hydraulic loading was investigated in this study. Other mechanisms of block failure such as damage to the embankment below the blocks exceed the scope of this study.

2.2. Bosun Buffalo blocks

The Bosun Buffalo block is a versatile Articulated Concrete Block (ACB) for erosion protection in water channels, embankment stabilization and pavements. The blocks have the benefit that they are modular, permeable, do not require on site-curing and promote vegetation growth. The unique block geometry and nibs create an interlocking matrix of blocks as shown in Figure 2-3. The nibs ensure effective interlocking but also create a flexible surface less prone to damage and easier to install on uneven surfaces. The blocks are effectively 400 mm by 216 mm in plan with a 100 mm thickness. According to the Bosun Catalogue the blocks have an average mass if 12.227 kg per block and an average density ranging from 2150 kg/m^3 – 2250 kg/m^3. During this study it was agreed with Bosun that the design mix be amended to a mass of 13.068 kg per block with a design density between

2400 kg/m^3 and 2500 kg/m^3. These values are a representation of the properties of the new scaled model blocks that was provided from Bosun. It is proposed that the minimum mass per prototype block should 13.1 kg, which will result in a packed unit mass of 177 kg/m^2 based on 13.55 blocks/m^2.

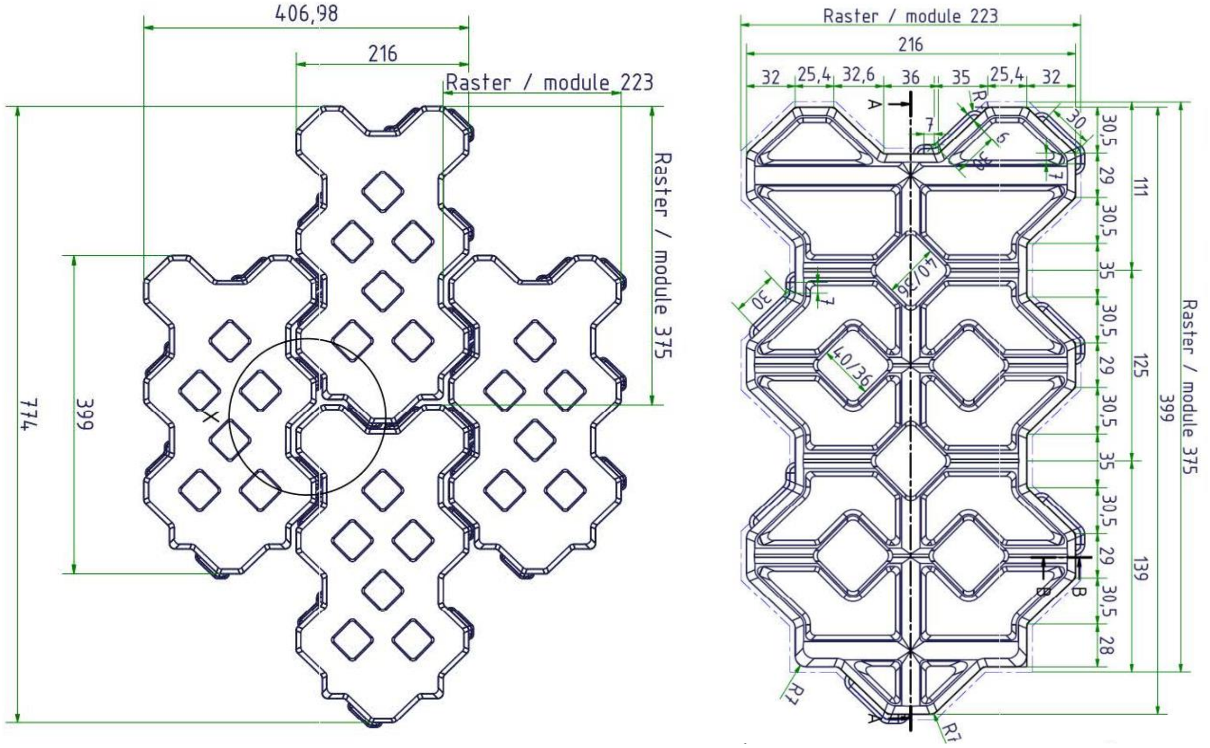

Figure 2-3: Prototype dimensions for the Bosun block module

The Bosun Group provided the SU Hydraulics Laboratory with high quality blocks at a 1:3 linear scale manufactured with the same density as the prototype blocks. The erosion protection blocks have to be scaled in the model study to enable simulation of flow velocities and depths similar to prototype conditions. The physical characteristics of a sample size of 50 blocks were inspected in the laboratory and a comparison of the average reported, prototype and model block characteristics are summarized in Table 2-1. For the statistical analysis of the variance in the physical characteristics between the provided prototype blocks and the scaled model blocks, refer to **Appendix A**.

Table 2-1: Comparison of physical characteristics for the prototype and model Buffalo blocks

Description	Prototype Average	Average scaled model	Average up-scaled model to prototype
Top length (mm)	387.240	126.88	380.64
Bottom length (mm)	399.100	131.41	394.23
Front width (mm)	215.680	72.44	217.32
Rear Width (mm)	215.860	72.52	217.56
Front thickness (mm)	102.000	32.51	97.53
Middle thickness (mm)	102.340	32.45	97.35
Rear thickness (mm)	102.740	32.28	96.84
Volume (m^3)	0.00531	0.00020	0.00542
Mass (kg)	13.470	0.484	13.080
Density (kg/m^3)	2539	2413	2413

The settling velocity of the blocks was determined experimentally in a 5.5 m high steel tank with a 1.5 m diameter in the Hydraulics Laboratory (Figure 2-4). To determine a representative settling velocity of the blocks the settling velocities were recorded of the same randomly selected model blocks that were inspected for their characteristics. Due to the complex shape of the block, a representative sphere diameter (d) with an equivalent volume were calculated with Equation 3. For the model blocks a representative d = 0.073 m was calculated.

$$d = \left(\frac{6}{\pi} V_{block}\right)^{1/6} \tag{3}$$

Where:
$V_{block} =$ volume of Bosun block.

The mean settling velocity of 48 model scaled blocks was found to be 0.822 m/s, with a standard deviation of 0.059 m/s, a minimum settling velocity of 0.715 m/s and a maximum settling velocity of 0.951 m/s (Figure 2-5).

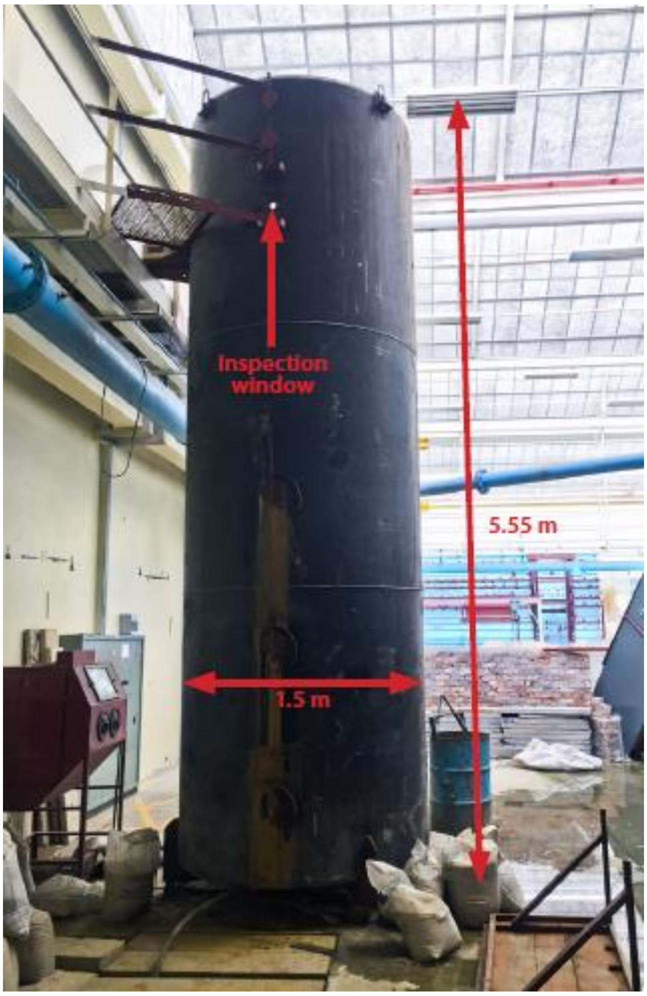

Figure 2-4: Steel tank used to determine the settling velocity experimentally

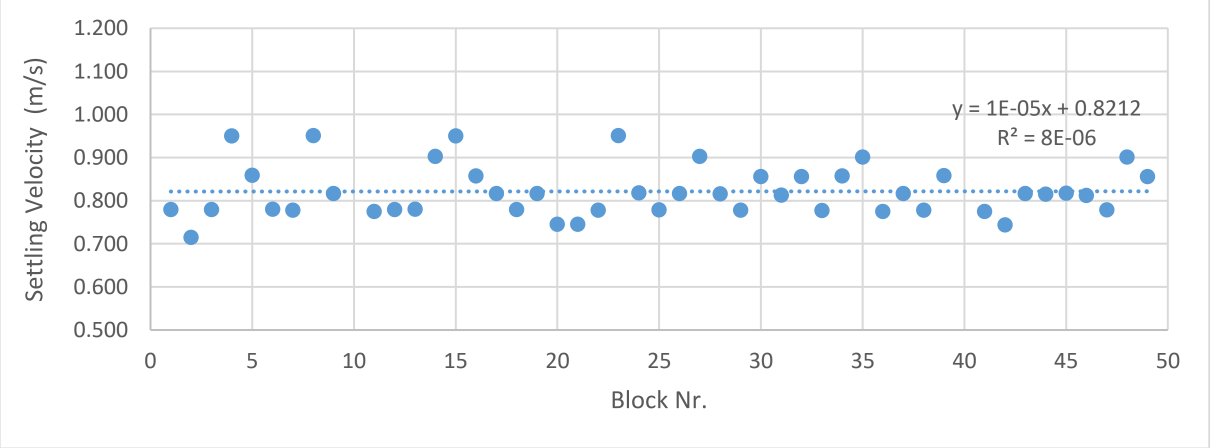

Figure 2-5: Settling velocities of the model scaled Bosun blocks as tested in the settling tank

3. Test setup and methodology

3.1. Test canal layout and construction

The tests were done in a 30 m long by 1 m wide flume with 3 different longitudinal bed slopes of 1:10, 1:20 and 1:30 (V:H). Figure 3-1 shows the schematic layout of the test canal layout of the physical model study. Water was pumped through a 600 mm ND mild steel pipe, through a calibrated flow meter and into the stilling basin at the upstream end of the flume. The inflow capacity was controlled with an inline gate valve while on the downstream end of the flume, water flowed out freely. The tailwater levels were not controlled as tests were only done in the supercritical flow regime. Downstream of the stilling basin, stacked hollow bricks straightened the turbulent flow, forcing it to be smooth and uniform in the vicinity of the blocks. Flow would then overtop a weir at Chainage 0 and enter the 6 m long test section at Chainage 3.

The test blocks were packed on a rigid sloping floor in the flume along the 6 m test section formed by a 40 mm thick cement plaster layer, covered with a scaled geotextile material which was glued to the plastered sloping floor. The blocks were installed according to the Bosun Group specifications from the downstream end of the test section proceeding in an upstream direction, hand packed in an interlocking fashion. Blocks against the side walls as well as the first 4 rows of blocks at the upstream end and last 4 rows at the downstream end of the test section were glued to the floor, preventing failure from occurring in these boundary areas. Figure 3-2 shows the blocks installed with the flow direction specified by the arrow. The blocks were packed in both directions, orientated with and against the direction of the flow for the 1:30 and 1:20 slope. The most stable orientation was used for the 1:10 slope tests, which was found to be the block noses pointing against the direction of the flow (Figure 3-2).

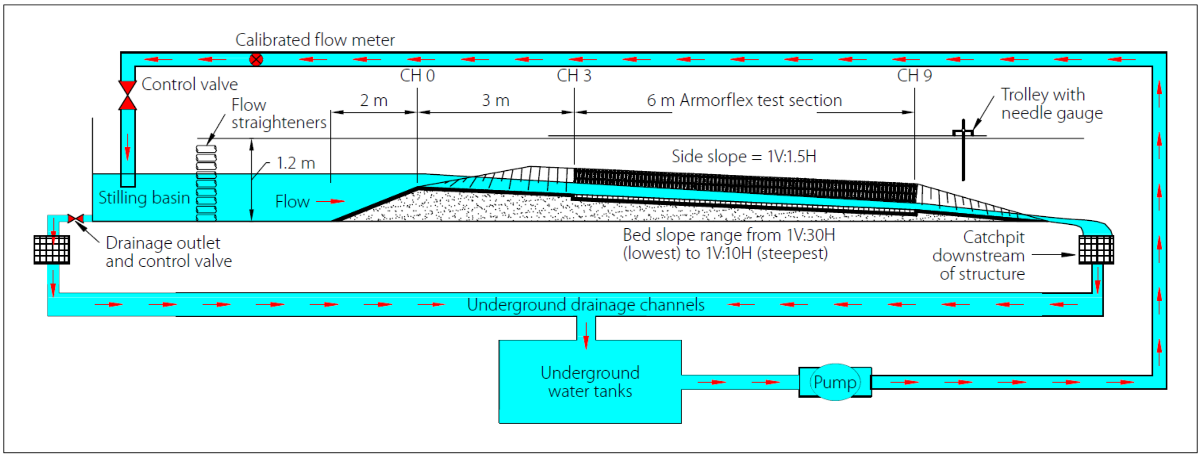

Figure 3-1: Test canal/flume layout in the hydraulic laboratory (not to scale)

Figure 3-2: Photograph showing the Bosun Buffalo blocks installed in the physical model for the most stable orientation (noses pointing upstream) on the bed slope of 1:10 (V:H)

3.2. Testing methodology and data collection

During each test, the maximum permissible flow before block failure had to be established. The flow was therefore stepped up at a rate of 20 l/s every 10 minutes until re-entrainment of the blocks was observed to identify the critical hydraulic conditions for incipient motion. Each test was repeated three times to determine the reliability of the results.

Both block orientations for the 1:30 slope were tested with a maximum model discharge of 740 L/s for the blocks aligned with the flow (noses aligned downstream) and a maximum laboratory discharge of 670 L/s for the blocks aligned against the direction of the flow (noses aligned upstream). No failure was observed for the 1:30 slope. Both block orientations for the 1:20 slope was tested with a maximum laboratory discharge of 380 L/s for the blocks aligned with the direction of the flow. A maximum laboratory discharge of 691.680 L/s was tested for the blocks with noses aligned against the direction of the flow with no failure being observed. Only the most stable orientation, i.e., blocks aligned against the direction of the flow with noses facing upstream, was tested for the 1:10 bed slope for discharges varying from 157 L/s to 163 L/s when failure of the blocks were observed for the three repeat tests.

Figures 3-2 to 3-4 show photographs of the 1:10 slope with the packed model blocks, the flow patterns at the maximum discharge when failure is imminent, and the blocks after failure, respectively.

Figure 3-3: Photograph of the flow patterns at the maximum discharge of about 160 L/s when failure is imminent for the 1:10 slope

Figure 3-4: Photograph of the test blocks after failure at 160 L/s for the 1:10 slope longitudinal bed slope

4. Analysis of test results

4.1. Physical model study test results

The hydraulic roughness of the Bosun blocks was calculated based on the model study tests for all the tests. The Manning n values were calculated for a range of discharges and bed slopes and are shown graphically in Figure 4.1-1. The Manning n values are a function of the flow depth and based on the trend line in Figure 4.1-1, typical n- values range from n = 0.024 s/m$^{0.33}$ at 0.1 m flow depth, to n = 0.031 s/m$^{0.33}$ at 0.7 m flow depth.

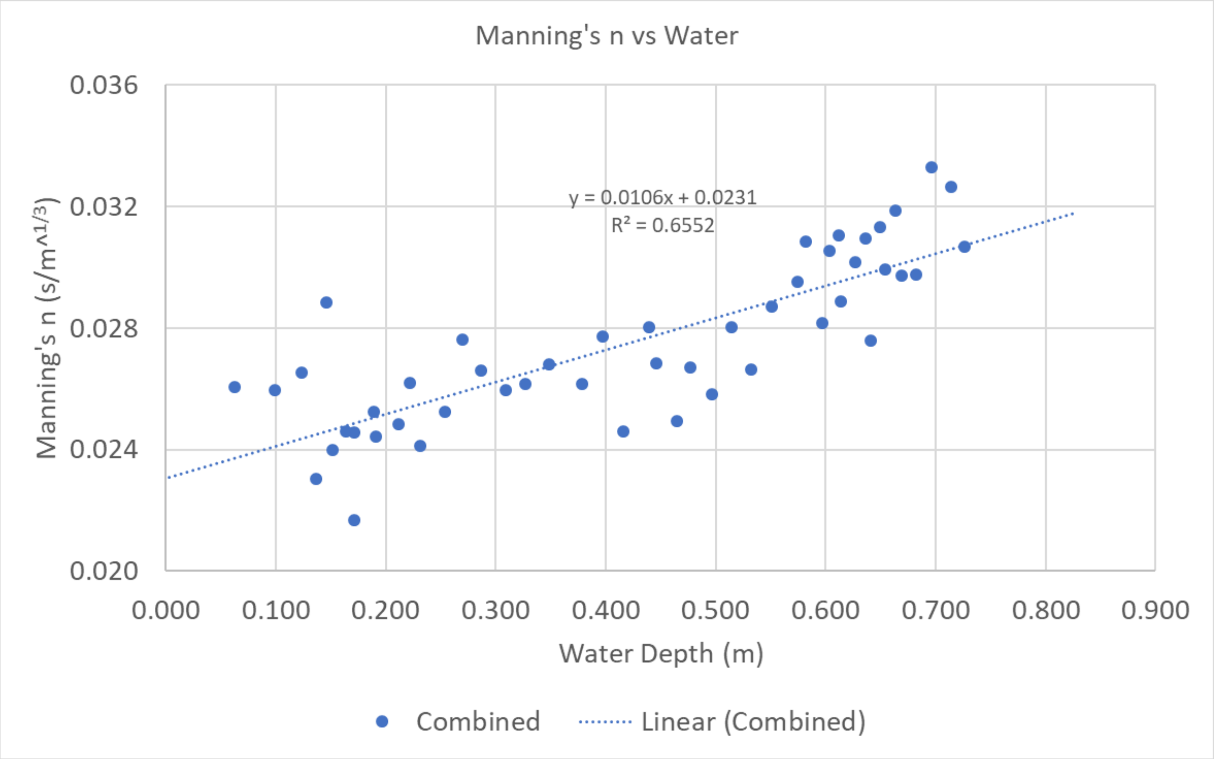

Figure 4.1-1: Observed Manning n values from the model study data converted to prototype data

The incipient motion hydraulic data for the Bosun block tests are shown in Table 4.1-1. Movement of the blocks aligned with their noses pointing upstream, was only experienced on the 1:10 (V:H) slope. Table 4.1-2 summarises the Liu diagram data which was plotted in Figure 4.2-2. The minimum Movability Number for the Bosun block tests of 0.327 was obtained from the 1:10 slope tests (repeated 3 times). The flatter slopes of 1:20 and 1:30 could not be tested to failure because the laboratory pump discharge capacity limit was reached, but the MN points for these tests are higher than for the 1:10 slope.

Table 4.1-1: Critical flow parameters at failure for blocks with noses aligned facing upstream (model values)

Test slope(V:H)	Q_m (m^3/s)	Flow depth y (m)	Froude number Fr	Local Energy Slope S_f (m)	System Conditions
Slope 1:30	0.670	0.242	1.80	0.031	No Failure - Max Lab discharge reached
Slope 1:20	0.692	0.229	2.02	0.058	No Failure - Max Lab discharge reached
Slope 1:10	0.157	0.074	2.49	0.100	Failed

Note: *Failure started at needle 3, 5.977m downstream of the crest of the sloped bed; the flow depth was taken at this location.

Table 4.1-2: Liu Diagram incipient motion parameters for Bosun block tests

Test slope (V:H)	Settling velocity Vss (m/s)	Local Energy Slope S_f (m)	Shear Velocity (V*)	Movability Number	Particle Reynolds Number (Re*)
Slope 1:30	0.822	0.031	0.272	0.332	1955
Slope 1:20	0.822	0.058	0.269	0.439	2620
Slope 1:10	0.822	0.100	0.269	**0.327**	1980

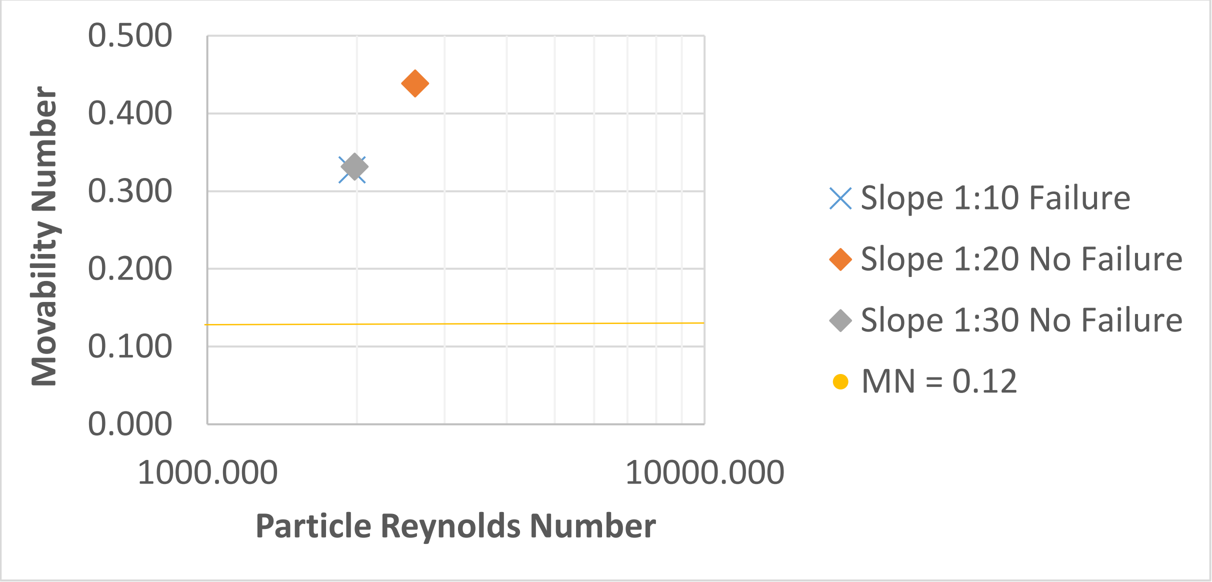

Figure 4.2-2: Modified-Lui diagram for all test scenarios of the Bosun Buffalo blocks

4.2. Comparison to incipient motion criteria of other materials

The incipient motion criteria for riprap (dumped rock) and Reno-mattresses have been thoroughly investigated by many researchers, mainly in terms of critical flow velocity and shear stress. Stoffberg (2005) and Langmaak (2013) managed to apply the streampower based approach of Rooseboom (1992) and Armitage (2002) to define incipient motion for riprap and Reno-mattresses in terms of Lui's movability number, while Delport et al (2021) investigated the incipient motion for Armorflex with Movability Numbers of 0.249 and 0.220 for Armorflex 140 and 180 respectively. Stoffberg (2005) suggested Movability numbers of 0.13 and 0.165 for riprap and Reno-mattresses respectively. Langmaak (2013) found that a critical Movability number of 0.18 can be used for riprap on steep bed slopes under non-uniform flow conditions which is close to the 0.17 recommended by Armitage (2017).

Table 4.2-1 and Figure 4.2-1 show the Bosun block movability numbers which are greater than those suggested above.

Table 4.2-1: Movability numbers for incipient motion for various erosion protection measures

Description	Movability Number
Riprap (dumped rock)	0.130
Reno-mattress	0.165
Armorflex 180	0.220
Armorflex 140	0.249
Bosun blocks	**0.327**

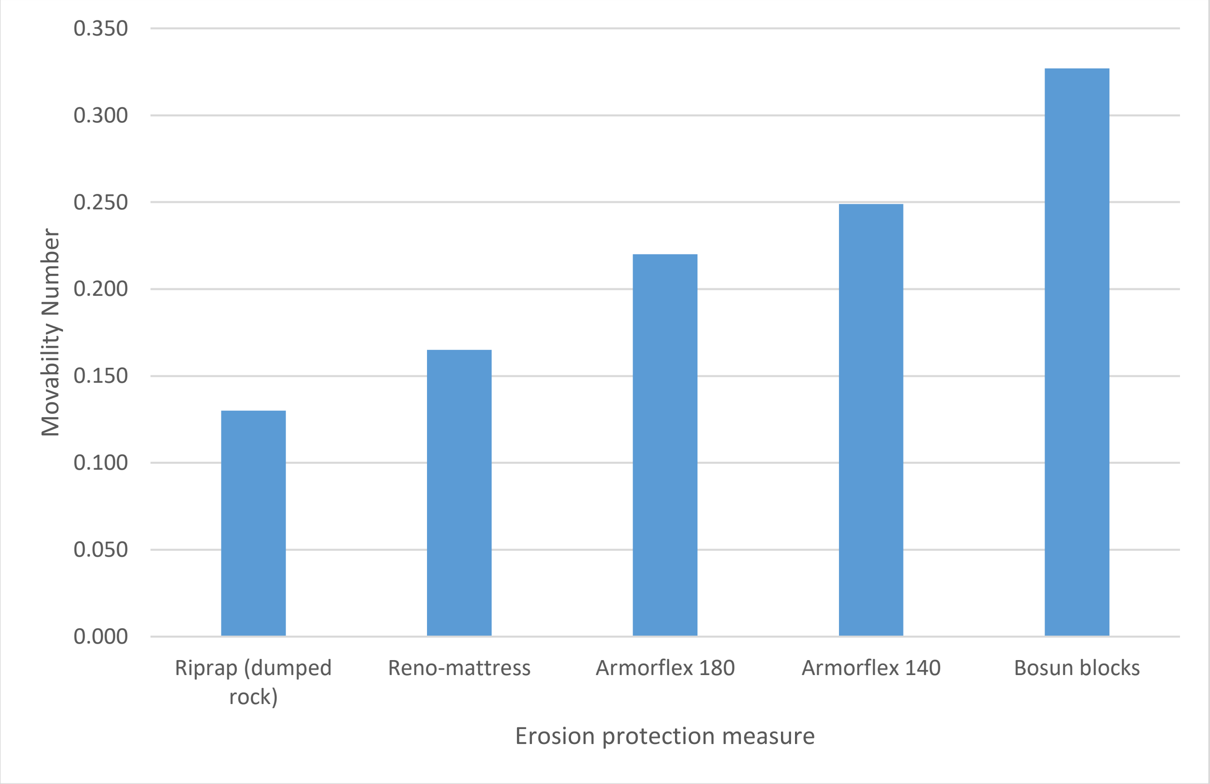

Figure 4.2-1: Comparison of incipient movability numbers for various erosion protection measures

5. Conclusions and Recommendations

The Movability Number for the Bosun blocks are greater than SANRAL's (2013) proposed Movability Number of 0.12 (for natural sediments like sand, gravel, boulders and rocks), rendering SANRAL's (2013) criteria conservative for design. The recommended Movability Number for the Bosun blocks are also greater than those recommended for riprap, Reno-mattresses and Armorflex mattresses. The combination of the shape of the Bosun blocks, their hydraulic roughness and relatively high mass per packed m^2, as well as the interlocking between blocks, are the factors which make the Bosun blocks hydraulically more stable than other typically used stormwater erosion protection measures listed above.

For hydraulic design purposes it is proposed that the design of erosion protection should have a margin of safety of at least 10% compared to incipient motion MN values of Table 4-3. Unless site conditions fall outside the limitations of this study, no additional safety factor needs to be applied to the recommended Movability Numbers with the 10% margin of safety hydraulic design.

6. References

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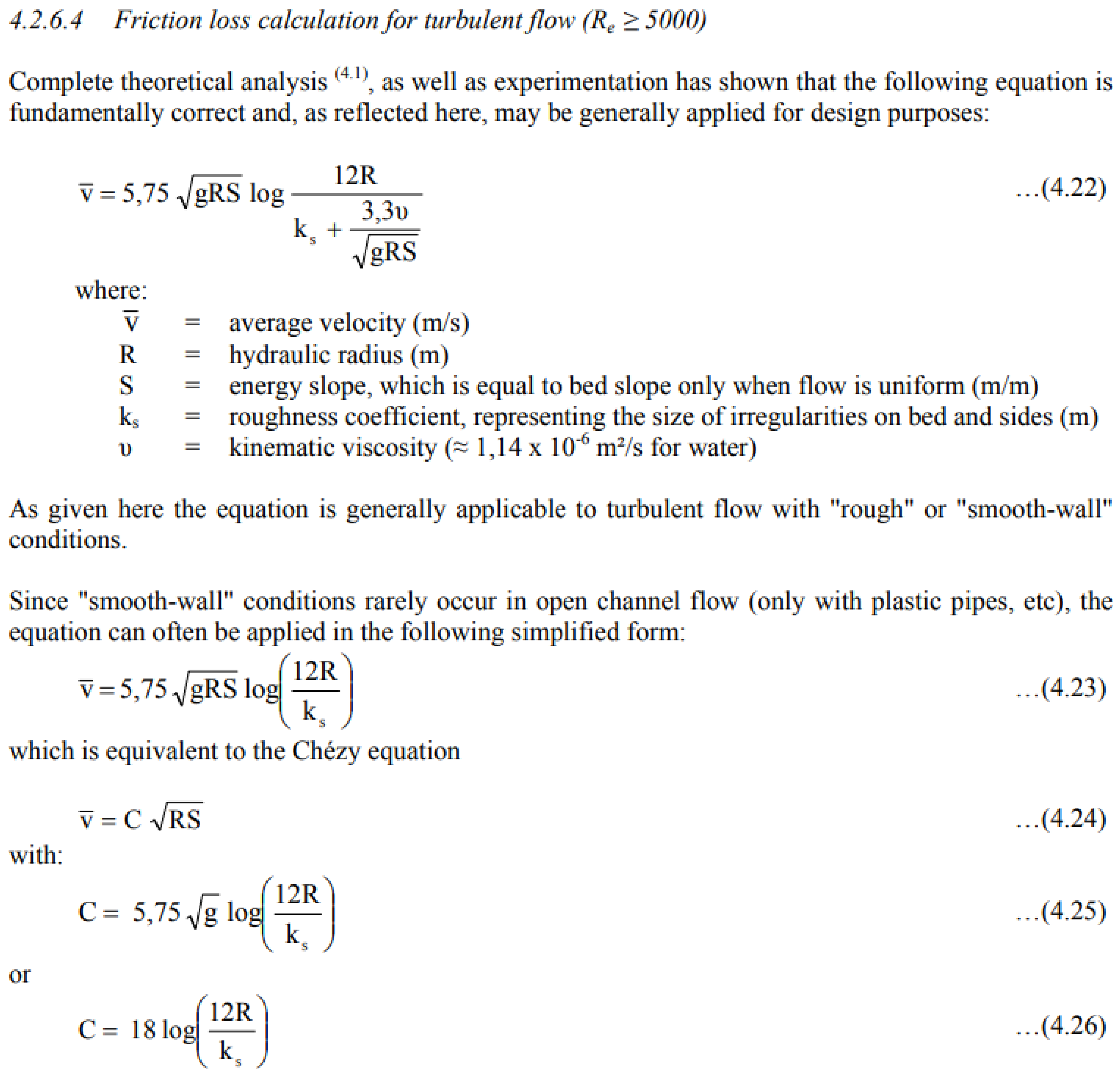
Appendix B: Calculation of hydraulic roughness when flow depth exceeds 0.7 m.

The Manning’s roughness coefficient presented in Fig 4.1-1 is limited to flow a flow depth of 0.75m.

From the physical model test results of your erosion protection blocks we propose that a constant hydraulic roughness of **ks = 0.05 mm (= 50 mm)** is used when the flow depth exceeds 0.7 m. For rough turbulent flow conditions the Chezy equations 4.24 and 4.26 below (SANRAL Drainage Manual, 2013), should therefore be used to calculate the uniform flow velocity and the discharge is then Q = V*A.

If the designer wants to use the Manning friction loss equation for flow depths > 0.7 m, the hydraulic roughness of 0.05 m should be used with the Chezy equation first to calculate the uniform flow velocity, depth and hydraulic radius (R), and then apply the Manning equation to solve the Manning n-value. Manning-n will not be constant for different flow depths > 0.7 m but is a function of the hydraulic radius. Manning’s equation V=R^(0.67)*S^0.5/n, with S = bed slope of canal = energy slope for uniform flow.

Chezy equation:



4.2.6.4 Friction loss calculation for turbulent flow ($R_e \geq 5000$)

Complete theoretical analysis [(4.1)], as well as experimentation has shown that the following equation is fundamentally correct and, as reflected here, may be generally applied for design purposes:

$$\bar{v} = 5{,}75\sqrt{gRS}\,\log\frac{12R}{k_s + \frac{3{,}3\upsilon}{\sqrt{gRS}}} \qquad \ldots(4.22)$$

where:

$\bar{v}$ = average velocity (m/s)
R = hydraulic radius (m)
S = energy slope, which is equal to bed slope only when flow is uniform (m/m)
k_s = roughness coefficient, representing the size of irregularities on bed and sides (m)
υ = kinematic viscosity ($\approx 1{,}14 \times 10^{-6}$ m²/s for water)

As given here the equation is generally applicable to turbulent flow with "rough" or "smooth-wall" conditions.

Since "smooth-wall" conditions rarely occur in open channel flow (only with plastic pipes, etc), the equation can often be applied in the following simplified form:

$$\bar{v} = 5{,}75\sqrt{gRS}\,\log\left(\frac{12R}{k_s}\right) \qquad \ldots(4.23)$$

which is equivalent to the Chézy equation

$$\bar{v} = C\sqrt{RS} \qquad \ldots(4.24)$$

with:

$$C = 5{,}75\sqrt{g}\,\log\left(\frac{12R}{k_s}\right) \qquad \ldots(4.25)$$

or

$$C = 18\log\left(\frac{12R}{k_s}\right) \qquad \ldots(4.26)$$