PAPER 14

OPTIMIZED FLEXIBLE LININGS FOR A MORE SUSTAINABLE RIVERBANK PROTECTION COMPARING TO THE TRADITIONAL RIPRAP

Blaise Jacob[1], Tasmira Saville[1], Devan Govender[1] & Anisur Rahman[2]
Maccaferri Africa (Pty) Ltd[1] & Officine Maccaferri S.p.A[2]

ABSTRACT

Riverbank erosion poses a persistent threat to municipal infrastructure in flood prone regions, driving up the cost of repairs and protection works along both natural and artificial watercourses. Traditional rip-rap linings demand large volumes of natural stone, incurring high expenses through quarrying and carbon intensive transport. This paper presents a specialised software suite that advances erosion control design by prioritising cost effective, performance-based solutions for longitudinal riverbank protections and grade control structures. The software integrates hydraulic modelling with material specific criteria, analysing cross sections under steady, uniform and turbulent flow conditions. It calculates critical hydraulic parameters including average velocity, shear stress and velocity beneath the lining, and compares them against material specific thresholds to verify structural stability and erosion resistance.

The tractive force method, preferred over the permissible velocity approach, is employed to assess the interaction between flow-induced stresses and channel linings, offering a more reliable representation of erosion dynamics and a physically consistent basis for design. Central to the cost savings is the incorporation of full-scale tests, conducted in accordance with ASTM D6460, on enhanced reno mattresses featuring pleated diaphragms and special vertical ties. These structural improvements deliver more than 50% greater flow dissipation and resilience than traditional gabions and reno mattresses, reducing natural resource requirements by over 70% relative to riprap. This translates directly into substantial reductions in procurement, transport and installation costs, as well as a lower embodied carbon footprint.

For grade control, the tool designs and verifies vertical drops, stepped and sloped weirs, and their dissipation basins across a range of flow conditions, performing both hydraulic and static checks to confirm compliance with relevant safety criteria. In the South African context, this accessible tool aligns with municipal priorities by empowering engineers to develop resilient and defensible designs. It significantly reduces material costs and natural resource consumption compared with traditional rip-rap linings, yielding substantial long-term savings for infrastructure owners while supporting labour-intensive construction methods.

By integrating empirical data from full-scale testing, robust hydraulic modelling and practical design tools, the software advances sustainable hydraulic engineering with demonstrable economic and environmental benefits, providing a transparent framework that strengthens decision making for riverbank protection in resource constrained and environmentally sensitive catchments.

1. INTRODUCTION

Riverbank and channel protection remains a central concern in municipal and hydraulic engineering, particularly in river systems characterised by high flow variability, morphological instability and increasing anthropogenic pressure. Across much of South Africa, watercourses are subject to highly seasonal and often flashy flow regimes, with intense convective storms producing rapid rises in discharge that mobilise bed and bank material. The economic and social consequences of uncontrolled erosion are considerable: damage to bridges, culverts, road embankments, water and sanitation infrastructure, and adjacent property imposes recurring costs on local authorities.

Longitudinal revetments are widely adopted to mitigate erosion and to preserve channel geometry. However, their design is governed by simplified empirical criteria that inadequately represent the physical mechanisms controlling erosion and structural performance. Among these, permissible velocity approaches remain common in engineering practice despite extensive evidence of their conceptual limitations. Classical hydraulic theory has long established that erosion potential is governed by boundary shear stress rather than by mean flow velocity alone, as set out in foundational works on open channel flow (Chow, 1959). Subsequent technical guidance issued by agencies such as the United States Army Corps of Engineers and the Federal Highway Administration has progressively endorsed shear stress based design criteria, particularly for flexible linings and erosion countermeasures (FHWA, 2005; FHWA, 2012; USACE, 1994).

Traditional rip-rap is widely used bank protection method in many South African applications. While effective where competent rock is locally abundant, rip-rap is resource intensive: it requires large quarried volumes, durable angular stone of specified grading, and carbon intensive haulage that becomes prohibitive where suitable material is remote from the site. Flexible rock-filled wire mesh revetments offer an alternative that uses substantially less stone for equivalent hydraulic performance, they can accommodate differential settlement and a substantial proportion of the installation work at site (mattress assembly, lacing and stone packing) is suited to labour intensive construction, consistent with the Construction Industry Development Board (CIDB) guidelines for labour intensive infrastructure projects under the Expanded Public Works Programme (EPWP).

In parallel with these developments, revetment technologies have themselves evolved. Modern rock-filled mattress systems (Figure 1), incorporate enhanced internal confinement (pleated diaphragms), optimised rockfill gradation and improved structural connections (vertical ties between base and lid), resulting in hydraulic behaviour that differs substantially from that of earlier generation systems. Applying outdated design thresholds to these modern systems introduces unnecessary uncertainty and may lead to either overly conservative or unsafe designs. This paper addresses that gap by combining recent large-scale experimental research on enhanced rock-filled mattress revetments with a

performance based hydraulic design framework (Di Pietro et al., 2021). The experimental results, obtained from controlled flume tests at Colorado State University (USA), provide material specific resistance thresholds based on physically meaningful failure mechanisms, which are then embedded in a computational design tool to enable transparent and consistent verification of channel and riverbank protection systems.

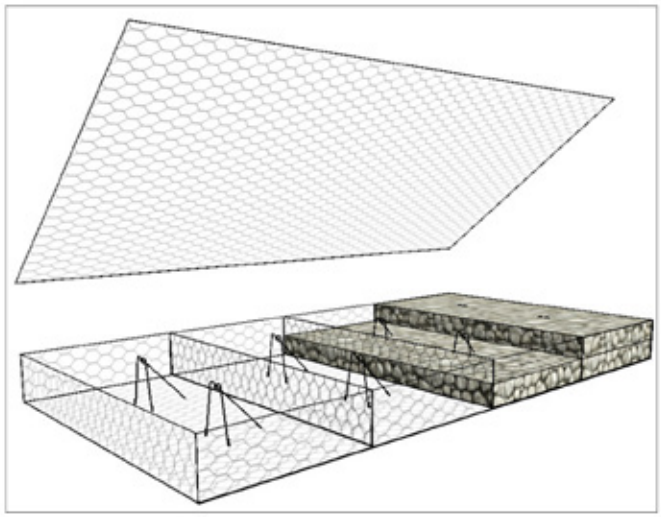


FIGURE 1: *Tested material: advanced rock-filled mattress manufactured in accordance with SANS 23-3*

2. EXPERIMENTAL BACKGROUND

Large-scale hydraulic testing performed at the Hydraulics Laboratory of Colorado State University provided the experimental basis for evaluating the erosion resistance of modern rock-filled mattress revetment systems under controlled yet realistic flow conditions. The programme was conceived to address limitations commonly observed in earlier studies, where failure criteria were often restricted to visible stone displacement and did not explicitly account for the response of the underlying erodible subsoil.

The tests were conducted in a flume equipped with an erodible bed, allowing direct observation of the interaction between flowing water, the revetment system and the subsoil (Figure 2). The experimental methodology followed the principles of ASTM D6460. Flow conditions were progressively increased until the onset of irreversible degradation of the protective function was observed. A defining feature of the approach was the adoption of a functional failure criterion based on the initiation of subsoil erosion beneath the mattress, rather than on superficial rearrangement of the rockfill. This distinction is critical: limited stone movement within confined compartments does not necessarily compromise the hydraulic performance of the revetment, whereas progressive subsoil erosion leads to loss of contact, increased seepage velocities and ultimately structural instability. The observations confirmed that subsoil response governs the ultimate performance limit of mattress-based revetments in high energy flow conditions.



FIGURE 2: *Views of the flume during testing*

The tested configurations incorporated structural enhancements relative to conventional mattress systems, including reinforced vertical connections between base and lid, internal diaphragms with increased confinement efficiency and optimised rockfill gradation. These features contributed to a more effective dissipation of flow energy within the mattress thickness and a reduction in stress concentrations at the interface with the subsoil.

Measured performance thresholds, expressed in terms of boundary shear stress, exceeded reference values reported for traditional mattress systems (Simons et al., 1984) by more than 50%, depending on mattress thickness, characteristic stone size and gradation (Di Pietro et al., 2021). The results (Figure 3) demonstrated that the hydraulic behaviour of these systems cannot be adequately described using simplified empirical limits derived for earlier generations of revetments. This finding is of direct practical relevance: it implies that design carried out using legacy thresholds will systematically underestimate the capacity of modern mattresses, leading to conservative over-specification and unnecessary cost.

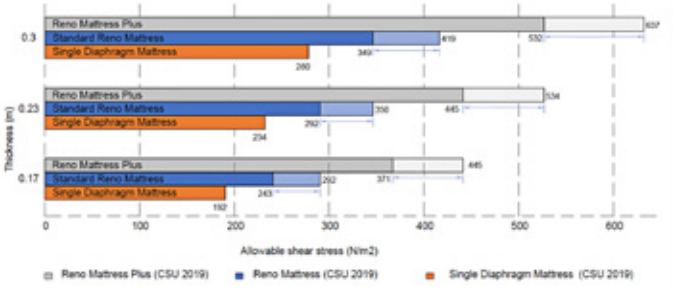


FIGURE 3: *Maximum shear stress values recorded at Colorado State University in 1984 and in 2019*

3. DESIGN METHODOLOGY AND CRITERIA

The experimental findings highlight the intrinsic limitations of design approaches based on permissible velocity, which remain widely used despite long standing theoretical objections. Mean velocity is not a direct descriptor of the erosive capacity of a flow, as it does not account for the combined effects of flow depth, hydraulic radius, turbulence structure and boundary roughness. This limitation has been recognised for decades in classical open channel hydraulics (Chow, 1959; USACE, 1994).

In contrast, the tractive force method provides a physically consistent framework by directly relating boundary shear stress to the resisting capacity of the protective lining. The approach is particularly suitable for flexible revetment systems, whose performance depends on the distributed interaction between flow induced stresses, internal confinement of the rockfill and subsoil support. Guidance documents such as FHWA HEC-15 and HEC-23 explicitly recommend shear stress based verification for channel linings and countermeasures, acknowledging that velocity based criteria may lead to unconservative or overly conservative designs depending on the hydraulic configuration.

The experimental programme at Colorado State University offers a critical contribution in this context by providing shear stress resistance thresholds calibrated against a realistic and conservative failure mechanism. Rather than associating failure with incipient surface instability, the experimentally derived limits correspond to the onset of subsoil erosion beneath the revetment. This definition aligns the design criterion with the fundamental purpose of riverbank protection systems, namely the prevention of progressive erosion and loss of structural integrity.

Tractive force theory

The acting shear stress is computed on the basis of tractive force theory (Figure 4).

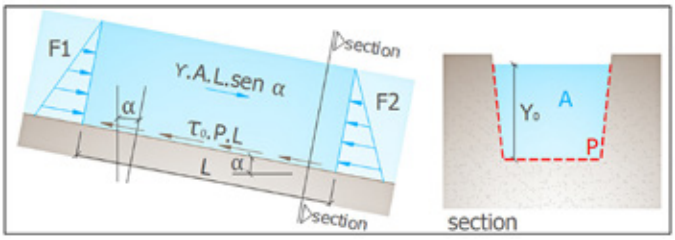


FIGURE 4: *Forces acting on the fluid mass (adapted from Porto, 2006)*

The acting forces are represented by the force of the water in the direction of the flow, upstream to the block, "F1" plus the block of water weight under analysis "γ_w·A·L·sinα", where "γ_w" is the specific weight of the water, "A" is the cross sectional area, "L" is the length of the block under analysis and "α" is the longitudinal angle. The resistant forces are represented by the force of the water against the direction of flow, downstream to the block under analysis, "F2" plus the resistant stress that is occasioned by the bed "τ_0·P·L", where "τ_0" is the shear stress and "P" is the wetted perimeter. For a steady uniform flow the system can be considered in equilibrium, therefore it is possible to say that F1 = F2. For α<6°, "sinα" can be approximated with the longitudinal slope of the channel "S". Adjusting the values, the shear stress can be calculated as "$\tau_0 = \gamma_w$·R·S".

Shear stress in channels is not uniformly distributed along the wetted perimeter (Chow, 1959), therefore the software can determine the reduction of the shear stress acting on inclined riverbank using the approach suggested by Olsen and Florey (1952). When a bank is divided in two or three subsectors, it is possible to estimate the actual shear stress coefficient according to the proportion of water height that is in contact with them (Figure 5).

Computed shear stress can be then compared with the allowable of the material selected, choosing from a wide database of erosion protection systems, including natural soils, or green systems, either in their initial stage of recovery (soil bioengineering techniques) or at their advanced vegetated stage (natural vegetation).

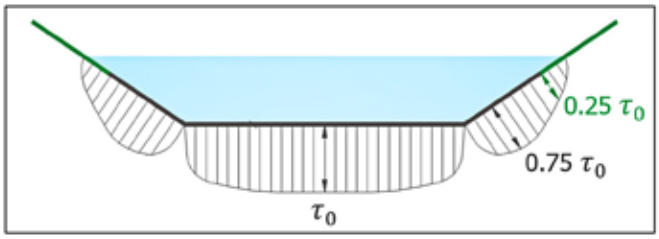


FIGURE 5: *Example of shear stress coefficient according to the height of the revetments*

4. COMPUTATIONAL FRAMEWORK

The experimental evidence described above was systematically incorporated into a performance based hydraulic design tool developed for the analysis and verification of channel and bank protection systems. The software performs one-dimensional hydraulic analyses on cross sectional geometries under steady and gradually varied flow conditions. Its primary objective is not merely to compute hydraulic variables, but to enable direct verification of protective linings against experimentally validated performance thresholds.

Within the channel and bank protection module, the software computes flow depth, wetted perimeter, hydraulic radius, velocity distribution and boundary shear stress for each portion of the cross section, allowing partial or full lining with different materials. Particular attention is given to the estimation of shear stress acting on banks and beds, and to the evaluation of velocities beneath flexible linings, which are critical for assessing the potential for subsoil erosion. These quantities are compared directly with resistance limits derived from laboratory testing, rather than with generic empirical criteria.

Most software used for river hydraulics can perform very complex analyses but requires correspondingly detailed and complex input data. The tool described here relies on a more practical approach. The designer selects the type of protection on each segment of a cross section from a material database; for each protection a shear stress resistance is associated. This allows practitioners to verify whether the chosen protection is sufficient to prevent erosion, while keeping the input requirements appropriate to the level of data typically available to a municipal design office.

The application of the framework does not eliminate the need for engineering judgement, particularly in reaches characterised by complex flow patterns, sharp curvature or hydraulic transitions. In such cases the one-dimensional representation of the flow may underestimate localised stress concentrations, and supplementary analyses or conservative design margins may be required, consistent with the recommendations in FHWA HEC-23 for stream-instability countermeasures. Nevertheless, within its domain of applicability the tool represents a significant improvement over velocity based approaches, providing a rational basis for the design of modern flexible revetments by clearly linking input assumptions, computed hydraulic parameters and performance criteria.

Grade-control structures

While the primary focus of this contribution is on longitudinal channel and riverbank protection, the same suite supports the design of grade control structures used to manage bed slope and stabilise the longitudinal profile of a watercourse. The tool checks a wide range of flow conditions and designs three types of gabion weir i.e. vertical drops, stepped weirs and sloped weirs (spillways), together with their dissipation basins, allowing the designer to evaluate and select the most suitable configuration. For the vertical drop weir, the hydraulic analysis determines the downstream uniform flow depth from Manning's equation, the backwater and jump geometry (including submerged weir conditions), and the downstream scour depth, with the stilling basin treated as unlined / lined / lined and excavated; a counterweir is sized only where the sequent depth requires it. The energy dissipated on each step of a stepped weir reduces the residual energy at the toe and therefore shortens the required stilling pool length, while for spillways the chute width is optimised against wall heights and excavation quantities. For each structure, the suite performs both hydraulic verification (energy dissipation, hydraulic jump, tailwater levels and downstream scour) and static verification (safety factors against sliding, overturning, seepage and filtration). The seepage check is particularly significant for these systems: because the porous gabion fill allows water to pass through the structure rather than around an impermeable base, the resulting flow paths produce strongly reduced velocities and hydraulic gradients near the toe; the safety factor against seepage and piping for a gabion weir is reported to be at least three times that of an equivalent concrete weir of the same geometry on the same foundation soil, even after allowing for long-term clogging. Consequently, the check

TABLE 1: *Comparison of traditional rip-rap and rock-filled mattress for riverbank protection*

Criterion	Traditional rip-rap	Rock-filled mattress
Design basis	Often permissible velocity	Shear stress, performance based on full-scale flume tests
Stone size required	Large stone owing to the low Shields coefficient	Smaller rock can be used to fill the mattress
Economy	Costly; heavy stone is seldom available locally	Cost-effective; can be filled with locally available, moderately sized stone
Behaviour beyond design forces	Initial stone movement is a limit state; a small additional force can progressively destroy the lining	Mesh confinement continues after initial movement; the unit may deform slightly but tolerates more severe conditions
Differential settlement	Not tolerated	Flexible; accommodates differential settlement without failure
Channel capacity	Large stone and high roughness reduce conveyance	Smaller stone and lower roughness enhance discharge capacity

is carried out using the method of critical hydraulic gradients rather than the conservative Bligh and Lane formulations derived for concrete. This capability is particularly relevant to South African stormwater and watercourse management, where steep urban catchments and erodible soils make bed level control a frequent requirement, and where permeable, flexible rock-filled structures provide an economical, constructible and hydraulically efficient alternative to mass concrete drop structures.

5. SOUTH AFRICAN APPLICATION AND COST ANALYSIS

The case for flexible revetments in the South African context rests on three linked arguments: resource efficiency, total cost of ownership (TCO) and constructability. Each is considered in turn below.

Resource intensity of rip-rap

Traditional rip-rap protection requires a competent, durable and well-graded angular stone placed to a thickness governed by the design flow. The quarried volume per unit area is high and, because suitable rock is not uniformly distributed, haulage distances are frequently long. Transport of dense natural stone is both costly and carbon intensive, and in many inland and ecologically sensitive catchments the environmental cost of opening or expanding a quarry is difficult to justify. By contrast, an enhanced rock-filled mattress confines a thinner layer of smaller, more readily available stone within a double-twisted (DT) steel wire mesh solution, mobilising the confinement of the structure rather than the mass of individual stones to resist the flow.

Material and resource savings

Because the experimentally validated shear stress resistance of enhanced mattresses exceeds that of traditional systems by more than 50%, an equivalent level of protection can be achieved with a markedly thinner section and a smaller characteristic stone size. In combination with the confining action of the mesh, this allows the stone requirement to be reduced by over 70% relative to a rip-rap solution designed for the same hydraulic performance. The reduction in quarried volume translates directly into fewer truck movements, lower fuel consumption and a smaller embodied-carbon footprint, while also reducing the pressure on local stone resources.

TCO and ease of construction

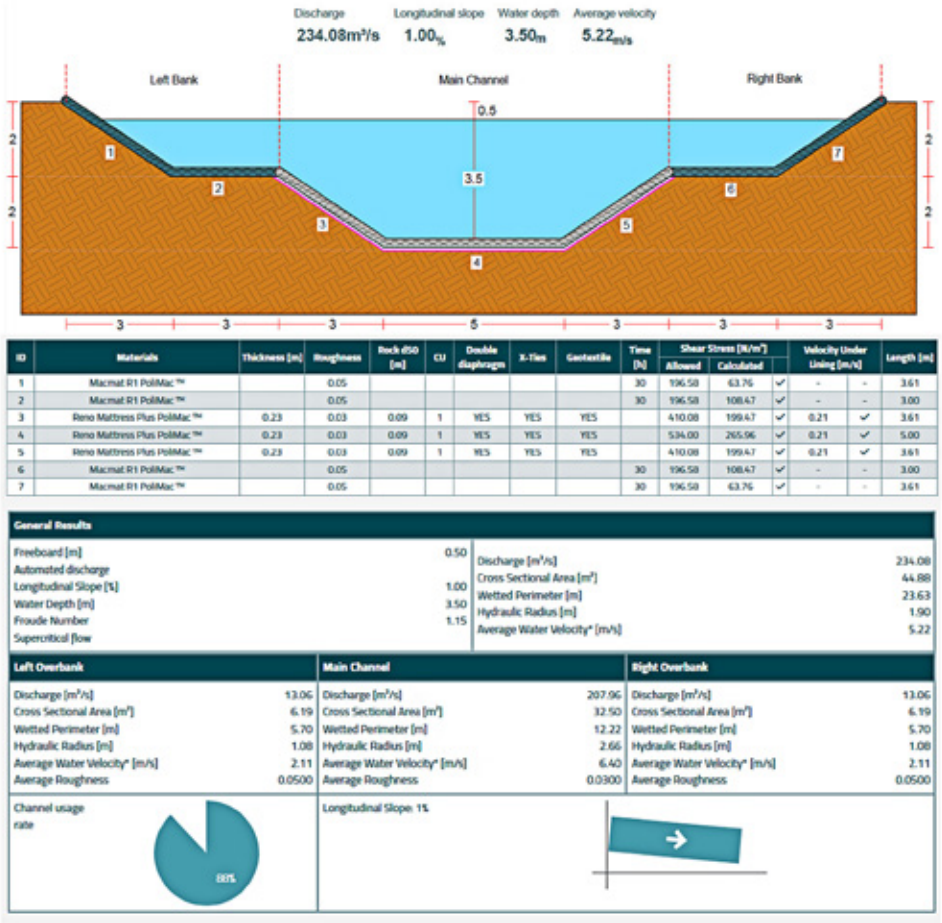
The cost of a riverbank protection scheme comprises procurement of materials, transport to site, installation and maintenance over the design life. Flexible mattress revetments reduce the first two components through the resource savings described above. The third component is particularly significant in the South African context: DT mesh products are well suited to labour intensive construction methods of the kind promoted under the Expanded Public Works Programme (EPWP), allowing a significant share of project expenditure to be directed towards local employment. Over the longer term, the flexibility of mattress systems allows them to accommodate minor settlement without catastrophic failure. The maintenance demand is therefore generally lower than that of a rigid system, which tends to fail abruptly once undermined.

Table 1 summarises the comparison between traditional rip-rap and rock-filled mattress across the principal decision criteria.

6. DISCUSSION

The integration of experimentally derived performance limits into a computational design framework represents a substantive step towards more physically grounded riverbank protection design. Unlike traditional approaches that rely on indirect indicators of erosive capacity, the adopted methodology relates computed boundary shear stresses directly to resistance thresholds calibrated against realistic failure mechanisms. The definition of failure based on the initiation of subsoil erosion, rather than superficial rock movement, is consistent with the functional objective of revetment systems and resolves ambiguities present in earlier studies, where limited stone displacement was sometimes interpreted as structural failure despite the absence of progressive erosion. Comparable concerns regarding failure definition for flexible linings are reflected in FHWA guidance, which emphasises the importance of subgrade stability in erosion control performance (FHWA, 2005; FHWA, 2012).

From a modelling perspective, the tractive-force-based framework allows a more robust treatment of partially lined sections and non-uniform geometries, conditions under which permissible velocity criteria are known to be unreliable. The methodology is not, however, without limitations. The reliance on one-dimensional hydraulic modelling means that local 3D flow phenomena, such as turbulence amplification at transitions and in sharp bends, are not explicitly resolved; as noted in classical and applied hydraulics literature, these effects can locally increase boundary stresses beyond cross sectionally averaged values (Chow, 1959; USACE, 1994). Performance also remains dependent on construction quality, in particular the integrity of the mesh, the connections and the rockfill placement. The framework should therefore be regarded as a decision-support methodology that enhances, rather than replaces, engineering judgement. Its primary contribution lies in improving the transparency and physical consistency of revetment design, and in giving municipal engineers a defensible, repeatable basis for comparing options on both technical and economic grounds.



ID	Materials	Thickness [m]	Roughness	Rock d50 [m]	CU	Double diaphragm	X-Ties	Geotextile	Time [h]	Shear Stress [N/m²] Allowed	Shear Stress [N/m²] Calculated		Velocity Under Lining [m/s]		Length [m]
1	Macmat R1 PolMac™		0.05						30	196.58	63.76	✓	-	-	3.61
2	Macmat R1 PolMac™		0.05						30	196.58	108.47	✓	-	-	3.00
3	Reno Mattress Plus PolMac™	0.23	0.03	0.09	1	YES	YES	YES		410.08	199.47	✓	0.21	✓	3.61
4	Reno Mattress Plus PolMac™	0.23	0.03	0.09	1	YES	YES	YES		534.00	265.96	✓	0.21	✓	5.00
5	Reno Mattress Plus PolMac™	0.23	0.03	0.09	1	YES	YES	YES		410.08	199.47	✓	0.21	✓	3.61
6	Macmat R1 PolMac™		0.05						30	196.58	108.47	✓	-	-	3.00
7	Macmat R1 PolMac™		0.05						30	196.58	63.76	✓	-	-	3.61

General Results

Freeboard [m]	0.50	Discharge [m³/s]	234.08
Automated discharge		Cross Sectional Area [m²]	44.88
Longitudinal Slope [%]	1.00	Wetted Perimeter [m]	23.63
Water Depth [m]	3.50	Hydraulic Radius [m]	1.90
Froude Number	1.15	Average Water Velocity* [m/s]	5.22
Supercritical flow			

Left Overbank		Main Channel		Right Overbank	
Discharge [m³/s]	13.06	Discharge [m³/s]	207.96	Discharge [m³/s]	13.06
Cross Sectional Area [m²]	6.19	Cross Sectional Area [m²]	32.50	Cross Sectional Area [m²]	6.19
Wetted Perimeter [m]	5.70	Wetted Perimeter [m]	12.22	Wetted Perimeter [m]	5.70
Hydraulic Radius [m]	1.08	Hydraulic Radius [m]	2.66	Hydraulic Radius [m]	1.08
Average Water Velocity* [m/s]	2.11	Average Water Velocity* [m/s]	6.40	Average Water Velocity* [m/s]	2.11
Average Roughness	0.0500	Average Roughness	0.0300	Average Roughness	0.0500

Channel usage rate

Longitudinal Slope: 1%

FIGURE 6: *Example of cross-section design using the software*

7. CONCLUSIONS

This paper has presented an integrated framework for the design of riverbank and channel protection systems that combines large scale experimental research with a performance based hydraulic design methodology (Figure 6). The experimental programme conducted at Colorado State University demonstrated that modern rock-filled mattress revetments with enhanced internal confinement exhibit substantially higher resistance to erosion than traditional systems, with measured shear stress thresholds exceeding legacy reference values by more than 50%. Significantly, performance limits were defined on the basis of the initiation of subsoil erosion, providing a failure criterion directly aligned with the functional purpose of revetment systems.

The translation of these findings into a computational design tool enables direct verification of revetment performance using boundary shear stress rather than simplified velocity based criteria. This is consistent with established hydraulic theory and contemporary technical guidance, and it provides a more reliable basis for designing flexible linings across a wide range of hydraulic conditions, as well as for the design and verification of grade control structures. For the South African municipal context, the approach offers a clear and quantifiable benefit: equivalent hydraulic protection can be achieved with over 70% less natural stone than traditional rip-rap, with corresponding reductions in transport, embodied carbon and cost, and with construction methods well suited to local labour intensive programmes (EPWP). Specifying advanced rock-filled mattresses manufactured in accordance with SANS 23-3 and selecting the steel wire mesh coating appropriate to the site environment level, allows the durability of the revetment to be matched explicitly to the design life of the works.

8. RECOMMENDATIONS

The design of flexible riverbank and channel linings should adopt shear stress based (tractive force) verification in preference to permissible velocity criteria, in line with classical hydraulic theory and current international guidance. This is best achieved through performance-based design tools that embed experimentally validated material resistance thresholds, so that the verification of a lining is traceable from the input assumptions, through the computed hydraulic parameters, to a defined performance criterion. On schemes where stone haulage, quarrying impact or total cost of ownership are significant, enhanced rock-filled mattresses should be evaluated as an alternative to rip-rap, with the resource, cost and embodied-carbon savings quantified explicitly at the options stage. Where these systems are adopted, the hexagonal double-twisted steel wire mesh should be specified to SANS 23-3, with the metallic and polymer coating selected according to the site environment level (C4 to CX), so that the assumed working life of the protection is matched to the design life of the works.

REFERENCES

ASTM International. (2019). ASTM D6460 – Standard Test Method for Determination of Rolled Erosion Control Product Performance. West Conshohocken, PA, USA.

Chow, V. T. (1959). Open-Channel Hydraulics. McGraw-Hill, New York, USA.

Di Pietro P., Mazzon N., Xu F. & Zhang C. (2021). Hydraulic performance of reinforced rock-filled mattress revetments. Proceedings of an international hydraulic engineering conference.

Federal Highway Administration (FHWA). (2005). HEC-15: Design of Roadside Channels with Flexible Linings. Hydraulic Engineering Circular No. 15, U.S. Department of Transportation, Washington, D.C., USA.

Federal Highway Administration (FHWA). (2012). HEC-23: Bridge Scour and Stream Instability Countermeasures. Hydraulic Engineering Circular No. 23, U.S. Department of Transportation, Washington, D.C., USA.

MacRA Design. (2023). Scientific Reference Manual: Channel and Bank Protection Module (Rev. 2.2). Maccaferri.

Simons D., Chen Y.H. & Swenson L.J. (1984). Hydraulic Tests to Develop Design Criteria for the Use of Reno Mattresses. Civil Engineering Department – Engineering Research Center, Colorado State University, Fort Collins, CO, USA.

South African Bureau of Standards (SABS). (2020). SANS 23-3:2020 / EN 10223-3:2013: Steel wire and wire products for fencing and netting – Part 3: Hexagonal steel wire mesh products for civil engineering purposes. SABS, Pretoria, South Africa.

U.S. Army Corps of Engineers (USACE). (1994). EM 1110-2-1601: Hydraulic Design of Flood Control Channels. Washington, D.C., USA.