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# Hydraulic Tests and Interpretation of Test Data for Reno Mattresses in Open Channel Flow

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**Abstract.** The efficacy of erosion control systems depends on preventing soil loss underneath and maintaining its integrity under the effects of the water flow. The paper presents the research results at the Colorado State University on the performance of double twisted wire mesh products, known as Reno Mattresses, used as soil erosion control systems. Mattresses were subjected to various flow conditions on a 10 m long flume placed on a soil layer. The performance against erosion was evaluated by assessing the effect of the stone motion inside the mattress combined with the condition of incipient soil erosion underneath, in relationship to the mattress thickness, the filling stone properties, and under variable hydraulic flow regimes. At the same time, confirming the stability obtained using the conventional tractive force design approach, the research results allowed to introduce a new performance limit based on incipient soil erosion underneath the revetment. Based on the research results, the authors propose to express the shear resistance of mattresses used as soil erosion control systems as a function of the filling stones' size, uniformity, unit weight, mattress thickness, and the presence of vertical strengthening elements.

keywords: Full scale tests, reno mattress, riverbank protection, hydraulics

## 1. Introduction

Reno Mattresses are cages, engineered from double twisted hexagonal woven steel wire mesh explicitly used for soil erosion protection commonly used on riverbanks. They are assembled and then filled with stones at the project site to form flexible and permeable, monolithic structures such as riverbank protection and channel linings for erosion control. Reno Mattresses are divided into uniformly partitioned cells by internal diaphragms.

Reno Mattresses were extensively tested in the open channel in 1984 at Fort Collins Laboratory of Colorado State University. During the 1984 test campaign, the stability of erosion control systems was evaluated mainly based on the degree of movement of the filling stones (rocks incipient motion criteria) and the deformations of the mattresses lid. The research allowed us to define allowable velocities and shear stresses which mattresses could withstand without exhibiting excessive deformations due to stones motion. Permissible shear stresses can be expressed as directly proportional to the filling stone size,



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their unit weight, and Shield's parameter.

More recently, the concept of soil loss underneath the mattress revetment was introduced. The stability of erosion control systems can be related to their ability to prevent soil loss underneath while maintaining their integrity under the effects of the flow.

The paper provides the overview of a research program to evaluate the performance of Reno Mattresses used as erosion control in open channels, which was carried out in 2019 by Colorado State University. This paper provides a testing description and results available up until December 2019. The experimental study aimed at monitoring erosion underneath the mattress until a soil loss threshold under the protection was detected. Furthermore, monitoring of stone movements inside the mattresses was also carried out. This approach is suitable for erosion protection systems, whose primary function is to avoid soil loss.

Mattresses were tested laid flat on a 0.20m thick soil layer in a 0.60x20m flume and on a 0.30m thick soil layer in a 0.90x10m flume, at increasing flow rates and varying gradients. Mattress performance against the erosion of the soil underneath was assessed by identifying the flow. The flow generates erosion underneath and assesses the effect of the stone motion inside the compartments as a function of its size, grading, uniformity, and mattresses thickness. The tests were carried out following the procedure described in ASTM D6460 – 12 (Standard Test Method for Determination of Rolled Erosion Control Product (RECP) Performance in Protecting Earthen Channels from Stormwater-Induced Erosion).

Additional scope of the study was to analyse performance response by varying mattress diaphragm spacing and type of internal partition. The analysis of the effects due to the stone motion inside the mattress, and relative soil erosion resistance underneath led to a formulation of a new design approach based on additional variables and mattress specific properties. Performance was found to be a function of the type of diaphragm partition, proper installation, the presence of the vertical connecting element, and grading and uniformity of the stone fill.



**Figure 1.** Top view of the of the flume during task 1.

## **2. Materials and Method**

The research was carried out at the Colorado State University (CSU) Hydraulics Laboratory located at CSU's Engineering Research Centre (ERC) in Fort Collins, Colorado. The hydraulics lab comprises many indoor and outdoor facilities that allow for a wide variety of hydraulics research. Water supply to outdoor and indoor research facilities is furnished by Horsetooth Reservoir, adjacent to the ERC.

Outdoor facilities are gravity fed from Horsetooth Reservoir with a capacity of approximately 170,000 acre-feet of water and a maximum static pressure of approximately 760 kPa providing up to 5.7 m<sup>3</sup>/s at some facilities. Indoor facilities are fed by a connected sump and recirculating pump system allowing for research year-round.

Three preliminary tasks were carried out to determine the best configuration of Reno Mattresses and stones to be used in the last and final task (task 4). Task 1 consisted of tests on 0.30m thick mattresses without stone filling. The objective of this test was to assess how much contribution the wire mesh alone would provide to the flow dissipation along the channel (Figure 1).

Tasks 2 and 3 were performed to measure velocity reduction within mattresses, filled with stones of different diameters and coefficient of uniformity Cu. The aim of tasks 2 and 3 was to measure the water flow dissipation effects through the mattress layer once filled with stones. During tasks 2 and 3, water flow was varied to keep the flow depth constantly above the mattress at different flume inclinations (Figure 2). Average water velocities along the channel were measured with sensor measurements throughout the testing.

A lesser flow rate required to achieve the same water head would correspond to a higher dissipation effect of the flow through the revetment. Results of tasks 2 and 3 showed that the smaller the rock size, the more flow was dissipated through the mattress.



**Figure 2.** Lateral view of the flume during task 2 and 3).

It was found that different diaphragm spacing did not significantly affect the flow in the mattresses and the energy dissipation. The water flow dissipation was found to be sensitive to changes in uniformity of the rock grading, for the same stones  $d_{50}$ . Mattresses filled with 10cm rocks and having  $Cu=1.5$  dissipated less flow compared to mattresses filled 10cm rocks and having a lower coefficient of uniformity ( $Cu=1.0$ ). Rock uniformity was found more impacting on the performance of the revetment compared to rock size. Observations during tasks 2 and 3 on the influence of rock size and rock uniformity led to selecting, as ideal stone range for task 4, rock filling with size  $d_{50}=9.5\text{cm}$ , and  $Cu=1.0$ .

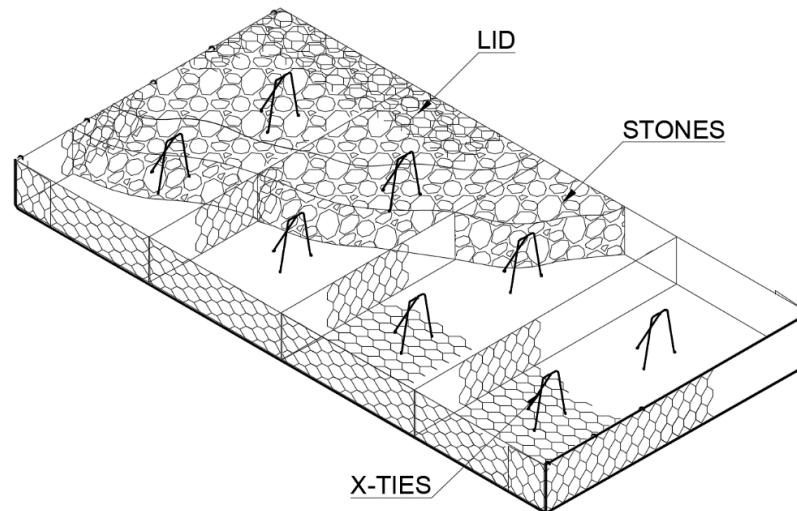
Based on the results obtained during the preliminary tasks 1, 2, and 3, the final task was performed on a 1.20 m wide, 10m long flume, using varying flow rates up to a maximum of 0.65m<sup>3</sup>/s, and at variable gradient from 15% up to 50% to test the performance of the three selected mattress configurations. The scope was to test the mattress when filled with the best performing rock grading obtained from tasks 2 and 3, despite the value conventionally assumed in the design practice as  $D_{60}/D_{10} = 1.5$ .

All tested mattresses were made from a 6x8 type hexagonal steel wire mesh manufactured in compliance with ASTM A975-21 and EN 10223-3. Mattress hexagonal mesh was manufactured with 2.2mm wire diameter, coated with a high abrasion resistance polymer (branded as Polimac®) with a



nominal thickness of 0.5mm. Mattress units had internal partitions positioned at 1m spacing along the channel longitudinal axis. Partitions were obtained by pleating the base of the mattresses and connecting the bottom corners by wire rings to form each partition as a double wall. Reno Mattress units were filled with rock having size  $d_{50} = 9.5\text{cm}$ , and  $C_u = D_{60}/D_{10} = 1.0$ .

Two different types of mattresses were tested, namely Double Diaphragm Reno Mattress and Reno Mattress Plus. The difference between the two types of mattresses is that Reno Mattress Plus had an additional special element connecting the bottom of the mattress and the lid, named x-ties (Figure 3)



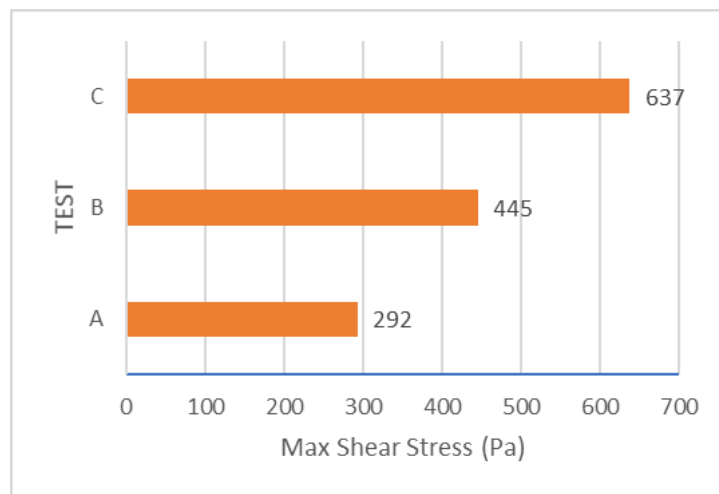
**Figure 3.** Schematic view of Reno Mattress Plus

Results of the tests allowed to correlate allowable shear forces of the mattresses with rocks size and grading. A summary of test configurations during task 4 is reported in Table 1.

**Table 1.** Summary of tested configuration during Task 4

Test	Mattress Properties				Filling Stones Properties	
	Thickness	Mattress Width	Diaphragm Spacing	Vertical Ties	$d_{50}$	$C_u = D_{60}/D_{10}$
A	0.17m (Double Diaphragm Reno Mattress)	1m	1m	No	95mm	1
B	0.17m (Reno Mattress Plus)	1m	1m	Yes	95mm	1
C	0.30m (Reno Mattress Plus)	1m	1m	Yes	95mm	1

During tests B and C, base and lid of the mattresses were secured together with an especially firm vertical wire connection, in a pattern of 2 connecting bracings per metre square of mattress surface. Mattresses used in test A, were manufactured with pleated diaphragms but without vertical bracings. A summary of shear stresses reached during the tests is illustrated in Figure 4.



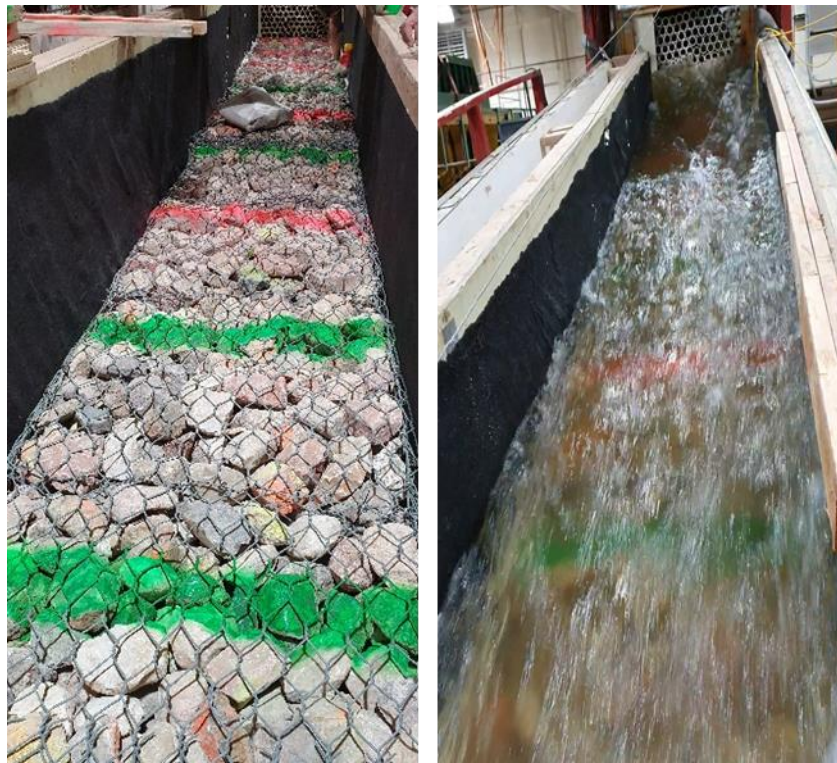
**Figure 4.** Maximum shear stresses measured during Task 4 for each tested configuration.



**Figure 5.** Sieves used for rock gradations.



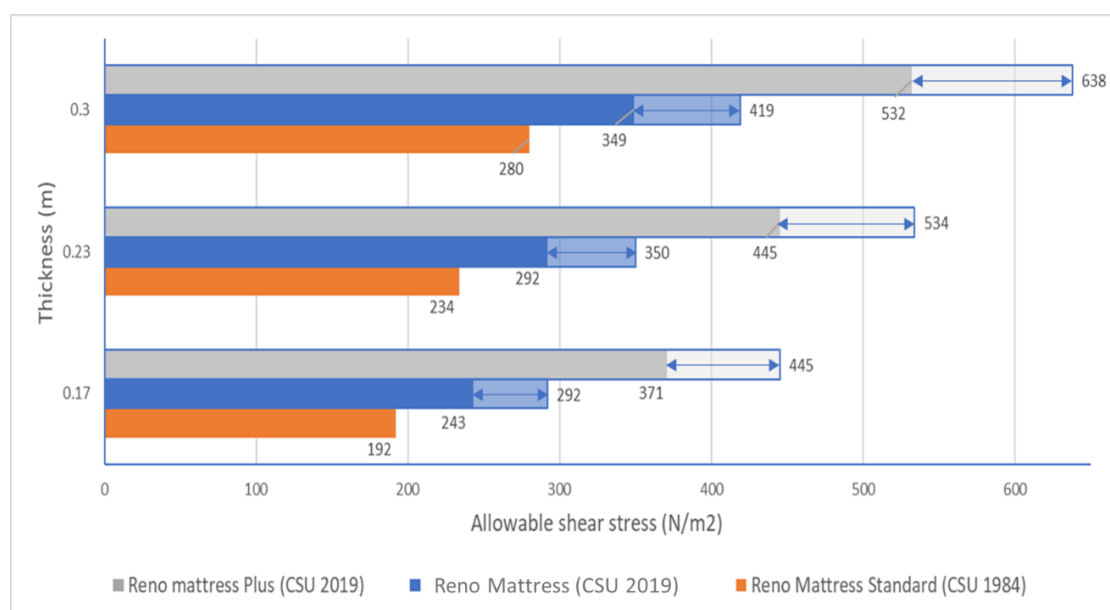
**Figure 6.** Reno Mattresses unit used during the tests.



**Figure 7.** Reno Mattresses during task 4 tests.

### 3. Results and Discussion

The experimental study object of this paper was carried out with mattresses with a “pleated” double layer of mesh in each compartment, filling the units with selected rock, and installing vertical bracings to firmly connect the lid to the base of the unit. Tests were performed in accordance with ASTM D6460-12.



**Figure 8.** Maximum shear stress values measured during CSU research in 1984 and 2019

Before the study object of this paper, the design of a riverbank protection with gabions or mattresses made of double twisted wire mesh was generally carried out considers the lining to be stable until minimal or no movement of individual stones occur inside the gabion or mattress, so keeping its protective function. The main design parameters typically used were mattress Shield's parameter and the rock fill size (Equation 1).

The test carried out in 2019 shows an increase in the limit allowable shear stresses compared to those obtained during full scale test run in 1984 at Fort Collins Laboratory of Colorado State University. This difference may be attributed to the new mattress configuration and to a different interpretation of the threshold values, which before were mainly based on stones motion and deformations. Shear stress values calculated in tests carried out in 1984 and recorded in 2019 are summarized in Figure 8.

Along with the new interpretation model, the difference in performance can be attributed to:

- 1) the use of vertical connections,
- 2) the use of a double pleated diaphragms,
- 3) the use of different rockfill (both in size and in uniformity).

With reference to Figure 8, the values on the left end of the range for Reno Mattresses (CSU 2019) and for Reno Mattresses Plus (CSU 2019) indicate the max allowable shear stress for units filled with rocks having  $C_u=1.5$ . While, the right end of the range indicates the max allowable shear stress for mattresses filled with uniformly graded rock ( $C_u=1.0$ ).

Among the variables, the improvement in the mattress's performance can be attributed to the presence of vertical connections. Such connection was later converted into an industrially manufactured component, X-Tie, where vertical bracing components are connected in a special U-Shape characterized by an even higher stiffness than the tested double connection. This system component is part of the Reno mattress Plus.

Based on the results of the research, and considering the effect of all the variables on the allowable shear stress, the authors are proposing a the following expression of the allowable shear resistance of a mattress when used as soil erosion protection:

$$\tau_{all} = f[f_1(d_{50}), \gamma_s, t, V_{ties}, C_u] \quad (1)$$

Where:

$\tau_{all}$  = allowable shear stress

$\gamma_s$  = unit weight of stone filing

$C_u$  = coefficient of uniformity of stone filling

$d_{50}$  = median stone filing size

$t$  = mattress thickness

$V_{ties}$  = presence of vertical ties

#### 4. Conclusions

Results of the research indicated that allowable shear stresses and water flow velocity used in design of open channels banks protection, following earlier research studies commonly referred to the tractive force theory (CSU test report 1984), could be considerably exceeded by introducing a new connection between Reno Mattresses base panel and lid, and by optimizing the size and gradation of the stone filling. The research allowed to define a limit of the performance of the Reno Mattresses by combining effects due to incipient soil erosion under the mattress and stone movements and at increasing flow rates. Based on the results of the research, and considering the effect of all the variables on the allowable shear stress, the authors have proposed a revised expression of the allowable shear resistance of a mattress when used as soil erosion protection (Equation 1).

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