POLITECNICO DI MILANO

School of Civil, Environmental and Land Management Engineering

Master of Science in Civil Engineering for Risk Mitigation (CERM)

"The use of geosynthetics as a countermeasure for scour at piers in rivers: experimental small case investigation"

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December 2021

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ABSTRACT

Scour countermeasures at piers have been created and innovated for decades. The advantages of integrating countermeasures to avoid reaching high expected scour depths have attracted considerable research interest as they can reduce the risk of the exposed infrastructures. In recent years, techniques including the use of new materials like geosynthetics received more attention and research, as the engineering of the materials allows to explore in detail the benefits of their development and implementation. Geosynthetics, in particular, are the core of this study since they have proved to improve factors like durability and resistance. Incoming pages summarize both innovative and conventional solutions of geosynthetic systems, unwrapping their uses and limitations.

Likewise, diverse countermeasures can reduce potential scour levels. One way is through the alteration of the flow, which includes solutions like dikes, vanes, sacrificial piles, or collars; however, most of the existing scour control measures are expensive. Therefore, another way to control the scour is through bed armoring countermeasures, including rip-rap, wire gabions, and geo containers. Generally, their objective is to form a layer at the area where the scour takes place and can withstand high shear stresses, so the bed materials underneath the armoring layer are protected from being scoured away. Based on their characteristics, the present study introduces a new countermeasure system named “geo-carpet,” which consists of a net placed on the bed sediment around the pier to withstand the consequences of the scour process.

The experimental campaign related to this work runs twelve tests in clear water scour conditions in free-surface flow. 2 out of 12 were unprotected tests, while the other 10 were tests using different types of geo-carpet as a countermeasure system against scour. These experiments were done with the variation of two principal parameters of the geo-carpets: the protected area and the net's mesh size. Furthermore, each test is surveyed in multiple points to create a digital surface that allows calculation of eroded and cumulative volumes of sediments, allowing further analysis of each type of geo-carpet.

Following the introduction of the topic, chapter 2 encompasses the literature review of the basics of clear water scour, live-bed scour, existing countermeasure methods, and countermeasures with geosynthetics. Chapter 3 presents the experimental facilities, the experimental campaign's description, and further details of the procedures to develop it. Meanwhile, chapter 4 breaks down the experiments where the geo-carpet is studied, analyzed and compared with similar methods of the reference studies. A final discussion and comments are made, including future research and improvements.

ASTRATTO

Per decenni sono state create e innovate contromisure al erosione localizzata alle pile. I vantaggi dell'integrazione di contromisure per evitare di raggiungere elevate profondità di erosione previste hanno suscitato un notevole interesse da parte della ricerca in quanto possono ridurre il rischio delle infrastrutture esposte. Negli ultimi anni, le tecniche che includono l'uso di nuovi materiali come i geosintetici hanno ricevuto maggiore attenzione e ricerca, poiché l'ingegneria dei materiali consente di esplorare in dettaglio i vantaggi del loro sviluppo e implementazione. I geosintetici, in particolare, sono il fulcro di questo studio poiché hanno dimostrato di migliorare fattori come la durabilità e la resistenza. Le pagine in arrivo riassumono soluzioni sia innovative che convenzionali di sistemi geosintetici, svelando i loro usi e limiti.

Allo stesso modo, diverse contromisure possono ridurre i potenziali livelli di erosione. Un modo è attraverso l'alterazione del flusso, che include soluzioni come dighe, alette, pali sacrificali o collari; tuttavia, la maggior parte delle misure di controllo del raschiamento esistenti sono costose. Pertanto, un altro modo per controllare il raschiamento è attraverso contromisure di armatura del letto, tra cui rip-rap, gabbioni di filo metallico e geocontenitori. In generale, il loro obiettivo è quello di formare uno strato nell'area in cui avviene il lavaggio e in grado di resistere a sollecitazioni di taglio elevate, in modo che i materiali del letto sotto lo strato di armatura siano protetti dall'essere raschiati via. In base alle loro caratteristiche, il presente studio introduce un nuovo sistema di contromisure denominato "geo-tappeto", che consiste in una rete posta sul sedimento del letto attorno al molo per resistere alle conseguenze del processo di erosione.

La campagna sperimentale relativa a questo lavoro esegue dodici prove in condizioni di acqua chiare con flusso a superficie libera. 2 su 12 erano test non protetti, mentre gli altri 10 erano test che utilizzavano diversi tipi di geo-tappeto come sistema di contromisura contro di erosione. Questi esperimenti sono stati condotti con la variazione di due parametri principali dei geotappeti: l'area protetta e la dimensione delle maglie della rete. Inoltre, ogni prova viene misurato in più punti per creare una superficie digitale che consente il calcolo dei volumi erosi e cumulati dei sedimenti, consentendo un'ulteriore analisi di ogni tipo di geotappeto.

Dopo l'introduzione dell'argomento, il capitolo 2 comprende la revisione della letteratura delle nozioni di base sulla erosione delle acque chiare, della erosione del live bed, dei metodi di contromisure esistenti e delle contromisure con i geosintetici. Il capitolo 3 presenta le strutture sperimentali, la descrizione della campagna sperimentale e ulteriori dettagli sulle procedure per svilupparla. Nel frattempo, il capitolo 4 analizza gli esperimenti in cui il geotappeto viene studiato, analizzato e confrontato con metodi simili degli studi di riferimento. Viene fatta una discussione finale e commenti, comprese ricerche e miglioramenti futuri.

RESUMEN

Las contramedidas contra la erosión en los pilotes en rios se han creado e innovado durante décadas. Las ventajas de integrar contramedidas para evitar alcanzar las altas profundidades esperadas de socavación han atraído un considerable interés de investigación, ya que pueden reducir el riesgo de las infraestructuras expuestas. En los últimos años, las técnicas que incluyen el uso de nuevos materiales como los geosintéticos recibieron más atención e investigación, ya que la ingeniería de los materiales permite explorar en detalle los beneficios de su desarrollo e implementación. Los geosintéticos, en particular, son el núcleo de este estudio, ya que han demostrado mejorar factores como la durabilidad y la resistencia. Las páginas entrantes resumen tanto las soluciones innovadoras como las convencionales de los sistemas geosintéticos, desenvolviendo sus usos y limitaciones.

Asimismo, diversas contramedidas pueden reducir los niveles potenciales de socavación. Una forma es mediante la alteración del flujo, que incluye soluciones como diques, aletas, pilotes de sacrificio o collares; sin embargo, la mayoría de las medidas de control de la socavación existentes son costosas. Por lo tanto, otra forma de controlar la socavación es a través de contramedidas de blindaje de cama, que incluyen rip-rap, gaviones y geo-contenedores. Generalmente, su objetivo es formar una capa en el área donde se produce la socavación y puede soportar grandes esfuerzos cortantes, de modo que los materiales del lecho debajo de la capa de protección estén protegidos de ser erosionados. Con base en sus características, el presente estudio introduce un nuevo sistema de contramedidas denominado “geo-alfombra”, que consiste en una red colocada sobre el sedimento del lecho alrededor del muelle para resistir las consecuencias del proceso de socavación.

La campaña experimental relacionada con este trabajo ejecuta doce ensayos en condiciones de socavación de agua clara en flujo a superficie libre. 2 de cada 12 fueron pruebas sin protección, mientras que las otras 10 fueron pruebas que utilizaron diferentes tipos de geo-alfombra como sistema de contramedida contra la socavación. Estos experimentos se realizaron con la variación de dos parámetros principales de las geo-alfombras: el área protegida y el tamaño de la malla de la red. Además, cada prueba se mide en múltiples puntos para crear una superficie digital que permite el cálculo de los volúmenes de sedimentos erosionados y acumulados, lo que permite un análisis más detallado de cada tipo de geo-alfombra.

Después de la introducción del tema, el capítulo 2 abarca la revisión de la literatura sobre los conceptos básicos de la erosión en agua clara, la erosión en lecho vivo, los métodos de contramedidas existentes y las contramedidas con geosintéticos. El Capítulo 3 presenta las instalaciones experimentales, la descripción de la campaña experimental y más detalles de los procedimientos para desarrollarla. Mientras tanto, el capítulo 4 desglosa los experimentos donde se estudia, analiza y compara la geo-alfombra con métodos similares de los estudios de referencia. Se realizan una discusión y comentarios finales, incluidas futuras investigaciones y mejoras.

1. Introduction

Since the beginning of human history, civil infrastructure systems have been an indicator of progress and improvement through time, becoming one of the most relevant matters for the engineering field. Nowadays, civil infrastructure systems are an issue that affects society on different scales, as in the case of connectivity, which allows economic growth. Modern engineers are focused more and more on research, development design, and construction of all kinds of infrastructures in a low-priced and optimum way. However, one of the most overlooked areas of infrastructure systems is maintenance, which plays an important role in the general scheme of any infrastructure management strategy, regardless of the country or city. For this purpose, engineers have been able to create innovative materials that smooth the difficulty of this task.

Civil infrastructure systems always are surrounded by multiple environments that could represent a risk to the infrastructure causing their failure. It creates the need to control the consequences of this failure in terms of connectivity, social, and economic impacts in the society or community. As described in the latest UNISDR's definition (2017), risk can be defined as a function of three factors: Hazard, exposure, and vulnerability. These cannot be controlled easily, but in the case of vulnerability, some infrastructures can be reinforced by installing a set of tools or systems that improve and maintain their performance over time. One representative example of civil infrastructures at risk, that applies especially to the condition of vulnerability are the bridges in hostile environments like rivers, or even worse, close to the sea. In this case, risk factors can be managed, for instance, using scour protection systems to reduce vulnerability caused by flood events.

Typically, in infrastructures like bridges, even if Hazard and Exposure factors cannot be changed due to their strong relation to the geographical location, the reduction in the vulnerability variable is valuable in the perspective of the systemic vulnerability related to any territory. The preparedness for any type of flood event or scour phenomena in representative bridges is driven by connectivity, increasing the likelihood of maintaining them in a good state for the after-emergency phase. Therefore, the redundancy in these territories can be preserved and augmented after any kind of hydrogeological event that endangers any populated area.

A comprehensive collection of bridge failure data worldwide gathered by Imhof (2004) [1] showed that natural hazards represent the first cause of bridge collapse, and among the natural hazard causes listed, flooding or scour are mostly responsible for these failures, as shown in the Figure 1. These statistics strengthen the ideal of modern engineering in the constant look for innovative ways to protect bridges and other infrastructures against future hazards.

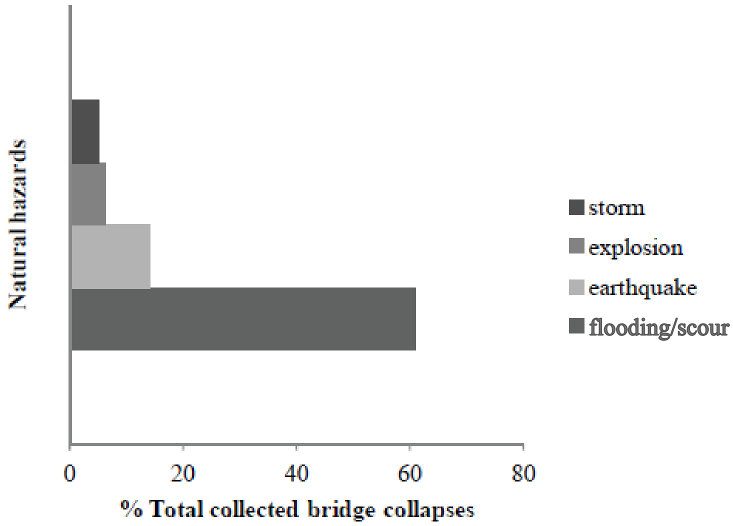


Figure 1. Natural hazards vs percentage of bridge [1]

One example is reported in the reference [2] Johnson, P. A. (1999) where the bridge at the route 51 over the South Fork Forked Deer River in west Tennessee failed due to local scour at the piers in 1973, even though abutments were well set back into the floodplain and were unaffected by scour. Second example is reported in reference [30] by Ettmer, Bernd, Franciska Orth, and Oscar Link, where the Figure 2 shows photographs of collapsed bridges during the 1998 "El Niño" flood event at the Piura River, Peru. During the flood, flow velocities reached values of 5–6 m/s, and the riverbed evidenced high mobilization with bed load layer of several meters overlapped with local scouring effects.

Figure 2. Collapsed bridges during the 1998 El Niño flood event at Piura River, Peru [30]

Bridge damage and failure can represent losses in terms of social connectivity, economic implications, and human lives. The federal highway administration [3] (Brice and Blodgett, 1978) reported that damages to bridges and highways from major regional floods in 1964 and 1972 amounted to about US$100 million per event; in New Zealand, a survey of roading authorities showed that scour caused by rivers results in roading expenditure of NZ$36 million per year (Macky, 1990). Therefore, over the years until now, civil engineering has created multiple systems to avoid losses due to bridge failure. Most of these new systems are supported by new material technologies, in particular the creation of geosynthetics.

As stated in the reference [4] (Wu, Hao, et al, 2020) geosynthetics are products made of synthetic or natural polymeric materials. The first reported employment of geotextiles is the nylon bags filled with sand used in the Dutch Delta works around 1956. As well, in the last 60 years, geotextiles have been widely used in geotechnical engineering. Nowadays, more than 1.4 billion square meters of geotextiles are used every year for multiple infrastructure projects. Geotextiles are considered cost-effective, durable, and easy to install.

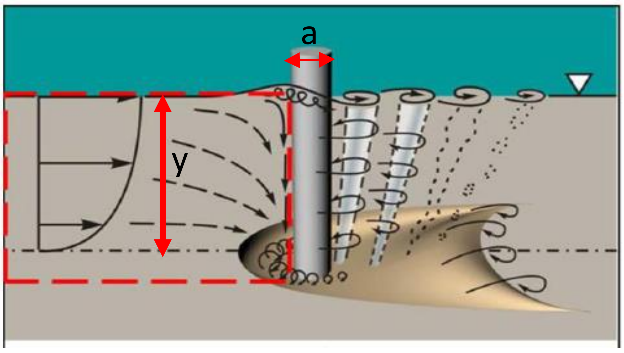
Objective

1. The objective of this study is to assess the use of the introduced countermeasure named "Geo-carpet" as a pile scour countermeasure in clear water conditions. To assess the "geo-carpet" an experimental campaign has been performed with multiple tests to evaluate the behavior of some parameters in the performance of the proposed countermeasure and compare the method with similar studies.

2. Literature Review

2.1. Pier scour phenomena

Piers scour phenomena result from the erosive action of flowing water when it has the strength to excavate and carry away material from around bridge piers and bridge abutments because of the flow alteration induced by the obstruction of the flow (Richardson and Davis, 2001) [5]. The scouring process can be described with the help of the pier flow field to give a clear idea of the movement of the sediments. It is divided into three categories described below, concerning the ratio between the pier width (a) and the flow depth (y) (ettema et al 2017) [6]. It should be highlighted that net width (a) includes the influence that pier shape and orientation of flow exert on the nominal diameter, and the values indicated in the following table are based on data trends delineating differences in the relationship between scour depth and y/a.

<table>
<tr><th colspan="2">Narrow Piers –(y/a≥1.4)</th></tr>
<tr><td>
Scour typically is deepest at the pier face</td><td>Flow approaching the pier decelerates, then, impacts against the pier's centerline, and then, strongly deflects both down and up the pier's face. These two vertical flows act almost wall-attached and flow along the pier's centerline, one directed up toward the free surface and the other down toward the bed. The down-flow is driven by the resulting downward gradient (below the still water level) of stagnation pressure along the pier's leading face. This downward gradient occurs because the velocity distribution of the approach flow is commensurate with a fully turbulent shear flow; that is, velocity generally decreases toward the bed. As the scour hole develops, the down-flow augments by the approach flow diverging into the scour hole. In addition to the vertical component of flow at the pier's leading face, flow contracts when it passes around the pier's sides. Local values of flow velocity and bed</td></tr>
</table>

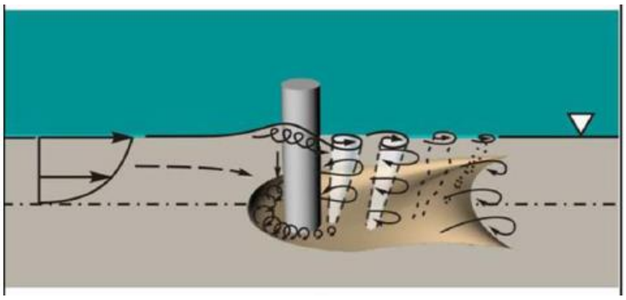
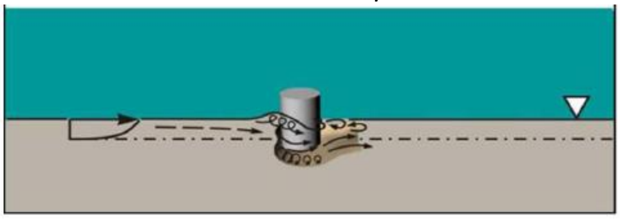
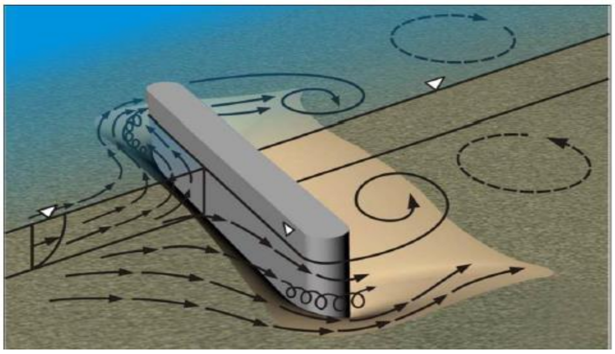
	shear stress, thereby increase around the pier's sides. The turbulence structures, together with local flow convergence/contractions, around the broad fronts and flanks of piers, are erosive flow mechanisms of primary importance.
Transition Piers –(0.2≤y/a<1.4)	
 *Transitional pier*  *Shallow transitional pier*	In the case of the transition piers, the flow field does not change representatively, but it changes in the way it develops. The figures show the flow-field adjustments indicating how the scour capacity of the flow field reduces. The down-flow at the pier face becomes less well developed because it has a shortened length over which to develop, whereas the up-flow (flow stagnation) associated with the bow wave remains essentially unchanged. The vorticity (circulation) of the large-scale turbulence structures (horseshoe vortex) that are aligned horizontally in the pier flow field weakens as the down-flow weakens. The vertically aligned turbulence structures, (wake vortices) also weaken owing to the increased importance of bed friction in a shallower flow.
Wide Piers (y/a<0.2)	
 *Scour typically is deepest at the pier side*	For wide piers, the flow approaching the pier decelerates, turns, and flows laterally along the pier face before contracting and passing around the sides of the pier. The down-flow at the pier face develops weakly and slightly erodes the foundation at the pier center plane, while the circulation of the necklace vortices reaches the peak at vertical sections situated around the sides of the pier. Flow velocities near the pier are the greatest where flow contracts around the pier's sides. Erosive turbulence structures now principally comprise wake vortices and the part of the horseshoe vortex system located in the scour region close to each side of the pier. The deepest scour occurs at the pier's sides.

Table 1. Description scour process. Reference [6]

The scouring process, like many others, is susceptible to the change of variables, in this case, differences in pier width, form and orientation, flow depth, and accumulations of debris or ice, that could alter the flow field and, in consequence, possibly enhance or weaken its erosive features. In addition, these factors can influence the scour depth, which is defined as the lowering of the riverbed level and is a measure of the tendency to expose bridge foundations [5] (Richardson and Davis, 2001).

Bridges are vulnerable to these phenomena because the bridge's piers support its superstructure, transferring design structural loads and flow-induced hydrodynamic loads. The transfer occurs via a set of end-bearing piles or friction-bearing piles connected to a pile cap, and the foundation material is permitting the pier column to sit on a slab footing. Piers fail when scour, together with structural and hydraulic loads, destabilizing their foundations.

To understand how the scouring mechanism can be managed or controlled is important to know that the development of the scour hole depends on the sediment bed motion. Based on this, two different scour regimes have been defined, clear-water scour and live-bed scour. The clear-water scour is the process where the material is removed from the scour hole, but not refilled by the approach flow. This condition occurs for mean flow velocities up to the threshold velocity for bed sediment entrainment. On the other hand, live-bed scour is the process where the scour hole is continually supplied with sediment by the approach flow. This happens because the process occurs when the velocity flow is higher than the threshold velocity for bed sediment entrainment.

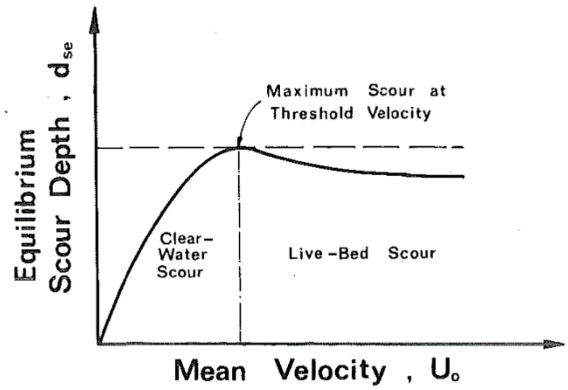


Figure 3. Equilibrium scour depth vs Mean Velocity [8]

Literature usually uses the ratio between these two velocities to delimit the threshold between the two regimes, thus, if the ratio is lower than 1 it is a clear-water scour process, otherwise is live-bed scour, as the figure shows. Moreover, the development in the scour hole is different for each type of scouring process. Clear-water scour is characterized by a scour depth that increases slowly and tends to reach a stable value. On the contrary, in the live-bed condition, the scour depth increases rapidly and reaches a value around the equilibrium time in which fluctuates. The figure 4 presented by Brandimarte et al, 2012 [9] shows in a graph these trends of scour depth for each type of scour.

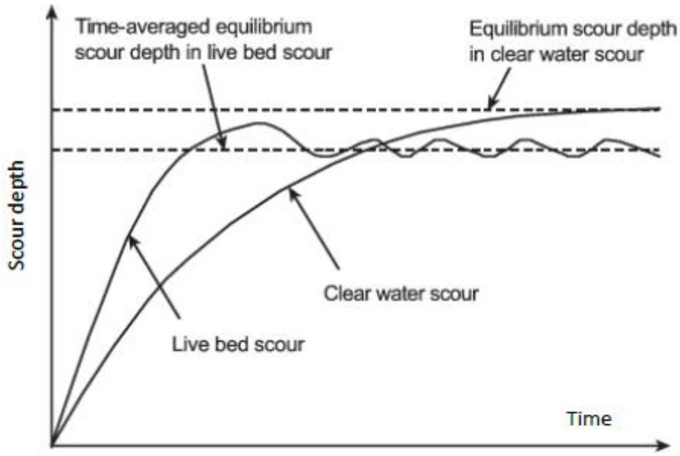


Figure 4. Scour depth vs time [9]

An interesting approach was developed by the research of reference [8] (Melville, 1984), which represents the scour depth variation parallel to the sediment bed motion stage. It also highlights the temporal decrease that exists in the scour depth (scour depth in the graph is normalized with the pier diameter) after the critic threshold (Uoc in the graph) due to the low velocities and initial stage of bed motion that generates lesser contributions to the erosion process.

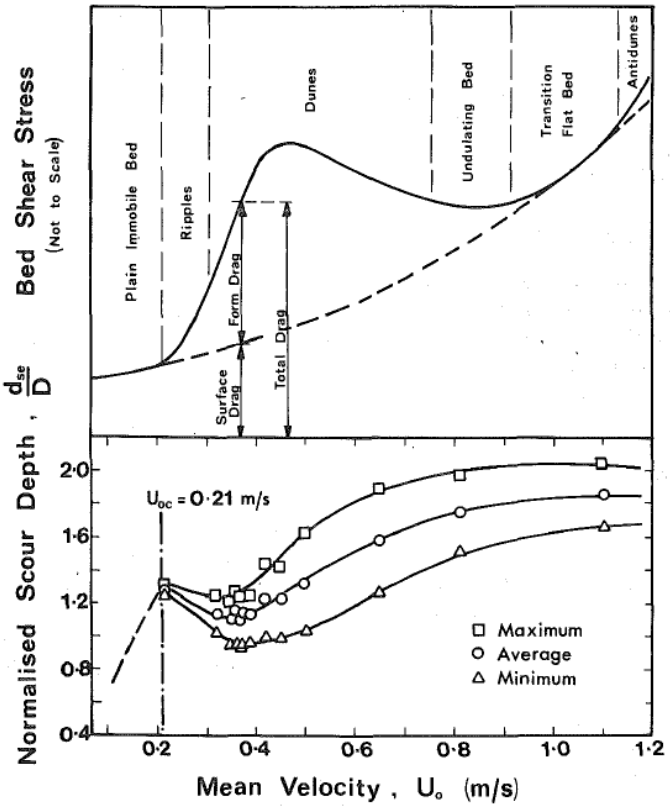


Figure 5. Bed motions vs mean velocity

2.2. Pier Scour countermeasures: A review of existing methods

Scour pile problems have always endangered the stability of the bridges, and the need to control this problem opens the opportunity to create multiple systems to preserve the integrity of the bridges. Traditional engineering has produced methods that attempt to control these phenomena with systems like rip-rap, wire gabion and collars.

2.2.1. Rip-rap

Scour holes created around the base of piers in many environments are related to the strong vortex motion previously described and the motion induced in the sediments. The most employed technique used by engineers to combat the erosional action is to use some form of armoring device on the bed named Rip-Rap. This system consists of a human-placed range of rocky material arranged along areas to protect them from scour and erosion. This system provides a physical barrier to resist the erosive powers of the flow and shield the pier's foundation exposition.

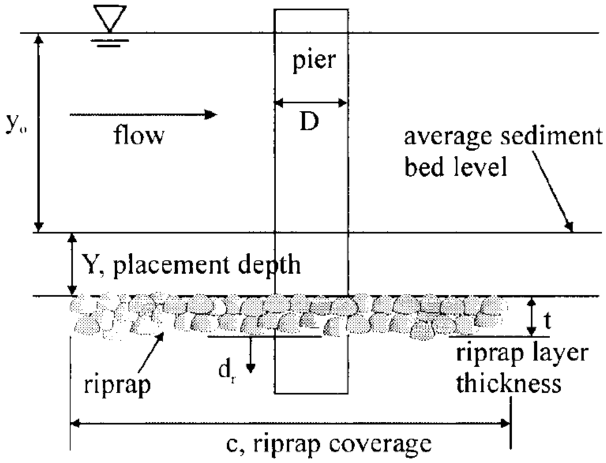


Figure 6. Rip-Rap scheme reference [11]

Later on, some research focused on the optimization of this system, and researchers like Chiew(1995)[7] and Chiew and Lim(2000)[10] showed that Rip-Rap protection is subject to some failure mechanisms that can destabilize the stones and lead to the complete disintegration of the protective armor. Nevertheless, as was explained before, the scour hole develops differently concerning clear-water and live-bed conditions. Thus, the failure mechanism changes depending on the condition at which the Rip-Rap is exposed.

In the case of clear-water conditions, the following failure mechanism can occur:

- *Shear failure:* This failure relates to the case where Rip-Rap stones are entrained by the flow.
- *Winnowing failure:* This failure corresponds to the case where the finer underlying bed material is eroded between the Rip-Rap stones under the action of turbulence and seepage flows.
- *Edge failure:* This failure matches the case where scouring at the periphery of the Rip-Rap layer undermines the armor stones.

In the case of live-bed conditions, the Rip-Rap layer is destabilized by the progression of bedforms past the pier. With the migration of large dunes, these bed level fluctuations cause the Rip-Rap stone to become unstable and possibly mobile, by removing the support of the bed beneath them. Two types of stone movement result. If the trough of the bedform is deeper than the bottom of the Rip-Rap layer, the Rip-Rap stones are undercut and slide into the region, possibly embedded at a deeper level. Once a stone is removed, the winnowing of the underlying sediment increases and the adjacent stones become more mobile. Alternatively, as the bedform approaches the pier, high levels of turbulence and correspondingly high shear stresses are induced for short periods. Rip-Rap stones can be plucked from the layer and transported to the lee of the pier.

The following figure represents the possible failure mechanism that can be present for both clear-water and live-bed regimes. The graph indicates the possible failure zones in terms of the flow velocity and the possible values of the variables D50 (median size of Rip-Rap stone particle distribution) and d50 (median size of bed sediment particle size distribution). The axis u_* represents undisturbed shear velocity while u_{*cs} symbolizes critical shear velocity for sediment bed material entrainment and u_{*cr} means critical shear velocity for riprap stone entrainment.

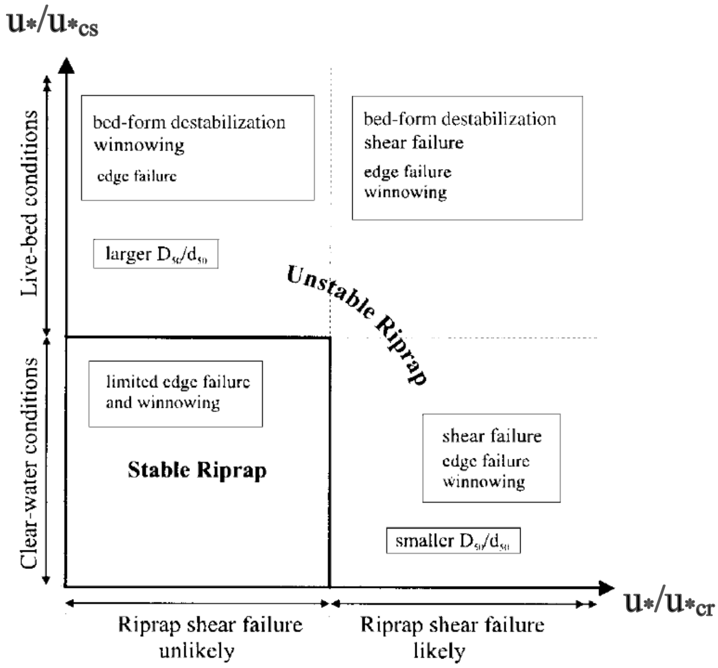


Figure 7. Rip-Rap failure mechanisms

The variation in the design procedure for this kind of system has changed over time to include every new research done to this day. However, some parameters can be highlighted as the most representatives to influence the Rip-Rap system. Mostly, the design procedures try to define the size of the Rip-Rap layer in terms of the flow velocity, pier width, median grain size of the Rip-Rap stone, and the median grain size of the sediments. In the table 2 [7] (Chiew,1995), there is a resume of design procedures that are still not universally accepted. Newest research like reference [11] tries to define the thickness of the layer of Rip-Rap more precisely, as this parameter has more repercussions in the performance of the Rip-Rap and can define the limit for an optimum design.

Method (1)	Minimum riprap size (2)	Extent of Riprap Layer: Length (3)	Width (4)	Thickness (5)
Gales (1938)	Not specified	5.5b^a	5b	Not specified
Bonasoundas (1973)	$D_{50}{}^{b} = 6 - 3.3U + 4U^2$ ($Ss^c = 2.65$)	7b, of which 2.5b is upstream of the upstream face of pier	6b	$b/3$
Neill (1973)	Presented in graphical form	Extend 1.5b in all directions from face of pier	Extend 1.5b in all directions from face of pier	$>2D_{50}$
Posey (1974)	Not specified	Extend 1.5–2.5b in all directions from face of pier	Extend 1.5–2.5b in all directions from face of pier	Not specified
Breusers et al. (1977)	$\frac{1.384U^2}{(Ss-1)2g}$	Not specified	Not specified	Not specified
Richardson et al. (1991)	$\frac{0.692(KU)^2}{(Ss-1)2g}$	Not specified	2b from face of pier	$>3D_{50}$

Note: D_{50} is in cm; U (undisturbed mean flow velocity) is in m/s; and K = 1.5 for round-nose pier and K = 1.7 for rectangular pier.
[a]Pier width.
[b]Median grain size of riprap stone.
[c]Specific gravity of riprap stone.

Table 2. Design approaches for Rip-Rap [7]

2.2.2. Wire gabion

A wire gabion is a wire net basket filled with stones. The system has some additional advantages such as flexibility, durability, permeability, and economy. Nevertheless, not so many studies have been done to assess the ability of wire gabions to act as an alternative to Rip-Rap in live-bed conditions. On the other side, multiple studies have been done for clear-water conditions showing interesting comparisons against Rip-Rap systems.

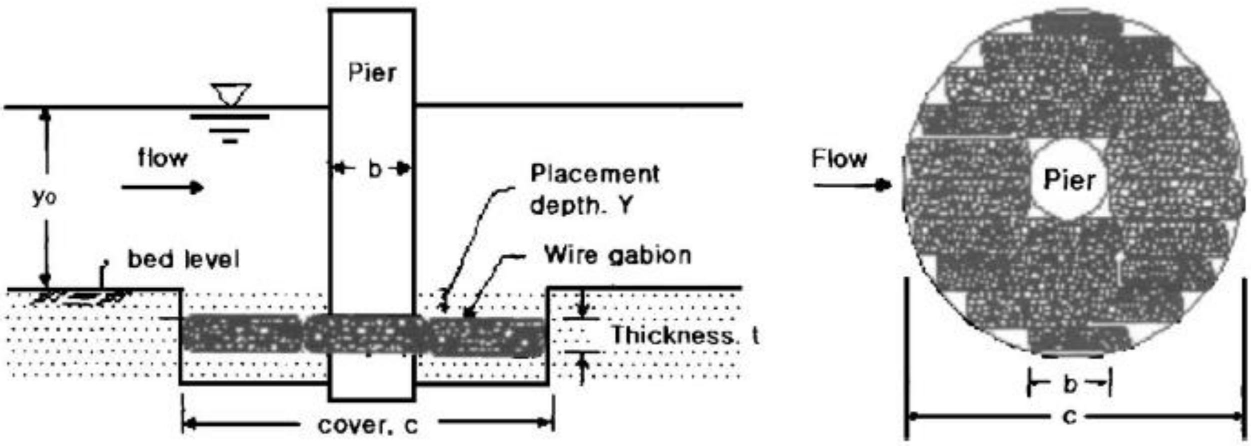


Figure 8. Wire gabion scheme [13]

The research by Yoon (2005) [13] shows that leaching phenomena are a failure mechanism for a wire gabion at clear-water conditions. It also includes how bed sediment particles in both side regions, upstream and close to the pier, are lifted through the interstices of wire gabions. Afterward, with the loss of this material near the pier the gabions were inclined towards it. This leached bed material was deposited downstream area beyond the gabion coverage. Moreover, after the increase of velocities, a secondary stage of failure may occur in the area between the pier and a distance of half the pier diameter from the pier, where the gabions became jolted. At last, with the presence of higher velocities, the jolted gabions were suddenly dislodged and swept away downstream beyond gabion coverage, leading to the displacement of the gabions resulting in a disintegration failure.

Secondly, other factors can affect the performance of the wire gabion system, as in the case where wire gabion is considered a very coarse bed material and the risk of peaking phenomenon of the critical entrainment velocity is possible. Scour depth or ratio between critic velocities in wire gabion increases with flow depth up to a limiting flow depth, above which there is no influence of flow depth. The peaking phenomenon observed at depths less than the limiting flow depth, which is inferred to occur mainly by lengthening of wire gabion and partly by complex flow conditions, becomes pronounced with increasing ratio of the length of the gabion and the thickness, resulting in the improved stability of wire gabions.

Lastly, the research by Yoon (2005) [13] demonstrates that wire gabions smaller than Rip-Rap provide equivalent protection. It implies cost-effectiveness, which means that wire gabion with the same volume as a Rip-Rap stone provides higher protection, indicating improved performance. Data from this study were compared with Rip-Rap experiments in live-bed condition from Lauchlan and Melville (2001) Reference [11]. It revealed that the two-layer gabion system has critical entrainment velocities greater than the three-layer Rip-Rap's by approximately 30% and the three-layer gabions by nearly 100%. Furthermore, comparisons confirmed that at given flow conditions, wire gabions that are smaller than Rip-Raps provide equivalent protection, implying to be cost-effective. Wire gabions with the same size as Rip-Raps provide better protection meaning improved performance as a countermeasure for scour protection in piers.

2.2.3. Collar

Collar is a type of countermeasure to control scouring around piers by diverting the downflow. It acts as an obstacle for the downflow and reduces the strength of the vortex. The efficiency of collars depends on the collar size and elevation. In other words, lowering the elevation of a collar also increases its efficiency as less flow penetrates below the collar resulting in a weaker downflow. In addition to lowering the scour depth, it helps to reduce the rate of scouring.

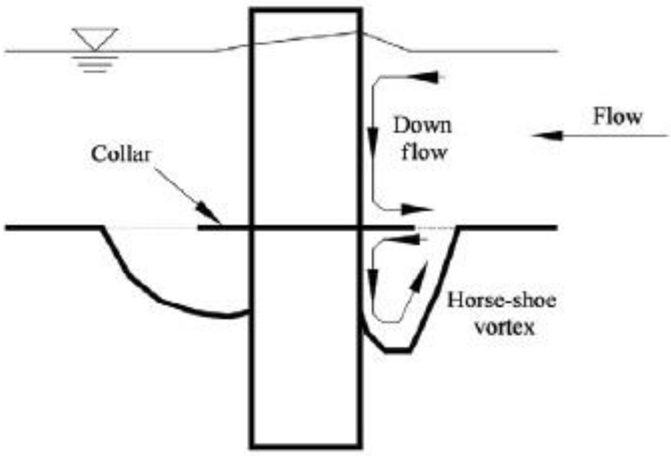


Figure 9. Collar scheme [15]

The research by Mashahir, M. B et al (2004) [14] demonstrates that in addition to reducing the depth of the scour hole, the application of a collar reduces the rate of scouring to a great extent. As used in the reference mentioned [14], a collar with an effective size equal to 3 times the pier diameter or pier width, installed at the bed level. It is shown that with a collar, the rate of scouring at the upstream face of the circular pier is very slow in the first 30 hours of the experiment. In this test, only 30% of the maximum scouring have occurred after 30 hours, whereas in the same amount of time, 98% of scouring occurred in an unprotected pier. It is also clear that a collar is more effective in reducing the scour rate than the pier foundation with a similar width and in the same elevation.

Some researchers have used a combination of different methods to protect the bridge piers. Chiew (1992) used the combination of a slot and Rip-Rap to decrease the bridge pier scouring. Zarrati et al. (1999) concluded that the scour depth could be controlled completely by a combination of a collar and Rip-Rap around a rectangular pier. Zarrati et al (2010) studied the combination of Rip-Rap and Collar to control the local scour around cylindrical piers.

This last research reflects some interesting relationships in the study of collars as a countermeasure for scour in piers. As a result, was found that the collar did not affect the reduction of the stable Rip-Rap size. Therefore, collars seem to be more effective in coarser Rip-Rap sizes as they protect the sides and upstream area of the pier. However, in finer Rip-Rap sizes, downstream of the collar, which is under the action of wake vortices, seems to be as critical as sides and upstream of the pier in removing Rip-Rap stones, and their results reflect multiple relationships between parameters of both systems. Lastly, the study establishes that using a collar reduced the Rip-Rap extent in the front and sides of the pier and that Rip-Rap volumes, with collar widths double or triple size than the pier width, are respectively 31% and 57% less than that for an unprotected pier.[15]

2.3. Pier Scour countermeasures with Geosynthetics

2.3.1. Geosynthetics

Over time civil engineering has found new ways to improve systems to build and maintain civil infrastructure thanks to the progress in the availability of new materials technology. There are multiple innovations in this field that contribute to improving concrete, steel, and others. Among these should be highlighted the creation of geosynthetics, which are products made of synthetic or natural polymeric materials, used in contact with soil, rock, or other geotechnical materials.

Geosynthetics include mainly: Geotextile, geogrid, geocell, geonet, geomembrane, erosion control mat, geosynthetic clay liner, and geo-composite [1]; of which geotextiles are used widely in geotechnical engineering, usually for at least one of the following functions: Separation, filtration, drainage, reinforcement, stabilization, barrier, and erosion protection.

About 98% of geotextiles consist of non-degradable polymers from the polyolefin, polyester, or polyamide family. The long-term use of geotextiles due to quite a few environmental factors such as wind, moisture, friction, and ultraviolet radiation, may cause the disintegration of synthetic polymer, resulting in the accumulation of microplastics in the surrounding environment. In addition, the application of geotextiles in geotechnical engineering may encounter complex environmental conditions such as complex acid-base settings, thus, the performance requirements of geotextiles will be higher (Wu, Hao, et al, 2020) [4].

Geotextiles should be developed towards high performance and multi-function, always improving their performance through the use of a green concept as the key factor, which can be appreciated in recent researches and developments. At least 50% of the total applications of synthetic geotextiles can be replaced by natural geotextiles. Moreover, the integration of optical fiber sensors into geotextiles opens a new path of possibilities towards the creation of “intelligent geotextiles”. These are expected to contribute to developing new monitoring systems for the geotechnical structures that ensure the discovery of the location of the ones with high failure and damage risk at an early stage (Wu, Hao, et al, 2020) [4].

A relevant aspect of geosynthetics systems used as scour countermeasures is their use as layer armors. These layers consist of single elements, like mattresses or continuous blankets that could be permeable or impermeable. The latter can be acceptable only when the development of excess pore water pressure below the layer can be ruled out. When the excess pore water pressure is caused by a groundwater table that is high compared to the level of the surface water, the excess pore water is steady. On the other hand, it could be an unsteady excess pore water pressure below the layer when a rapid drop of the surface water pressure is due to waves or a drawdown. Consequently, for all scour countermeasures, a permeable cover layer is recommended even if these configurations could cost more effort and money, since the benefit as a general balance is positive for this kind of case.

In addition, the armor layer of the scour countermeasure requires minimizing the thickness of the layer to increase the cost-benefits for some configurations. In other cases, the arrangements of the geosynthetic must be placed linearly and with a minimum thickness, while providing the best resistance possible against the erosive forces of the current. One method applicable to these systems is improving their resistance by connecting the elements of the layer. The general idea is to use smaller and often cheaper elements but to gain high resistance against the hydraulic load by connecting them to continuous layers. For example, geosynthetic bags filled with sand are very suitable, or geosynthetic mattresses can be a good choice even though is very difficult to place them without gaps.

The scouring process requires a major effort to be stopped completely, and usually small scour holes at the borders of the scour protection are inevitable and accepted if they are within the threshold. Thus, the scour protection system must be flexible to guarantee adaptation in the edges otherwise with rigid systems it has to be guaranteed that erosion will not develop either below or beside the armor layer, which can be hardly accomplished. This extends to all the elements of the armor layer including the fill, filter, and armor. For example, as can be seen in figure 10 a scour countermeasure is formed by geo-containers as a filter and filled with Rip-Rap as a cover layer. This system can adapt to the geometry given and can keep changing geometry due to the hydrodynamic forces [12].

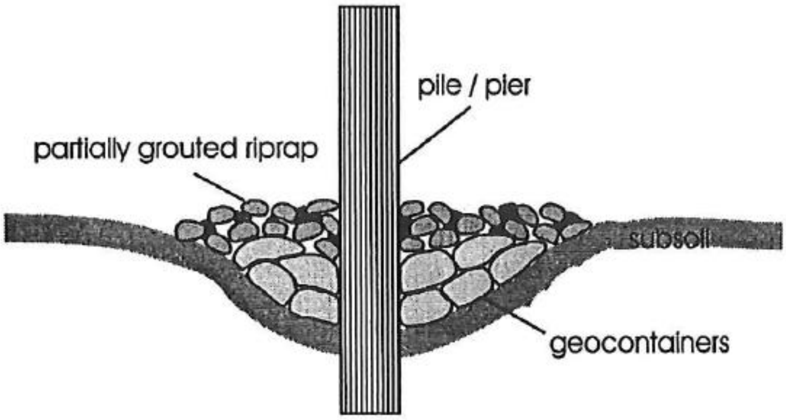


Figure 10. Example of flexible scour countermeasure. Reference [12]

Finally, is essential to highlight that each kind of geosynthetic has its disadvantage in the placement of each one. For example, in the case of geotextiles working as filters, the placement depth is limited to 20 meters. Likewise, mattresses usually are assembled in dry conditions and placed by special cranes. Only geosynthetic concrete mattresses are filled on-site, but to place the geotextile cover, the same difficulties as with geotextiles filters arise.

2.3.2. Pier scour protection with geosynthetics

If expected scour development exceeds a tolerable limit, then there is a need for countermeasures to avoid reaching this limit. Either the action must be reduced and use the called “active” measures, or the resistance must be increased and use “passive" measures. In both cases, geosynthetics can be rather beneficial. Nevertheless, there is another path to follow where the action is changed, through the alteration of the flow pattern in such a manner that scouring is stopped. This can be done for instance, by river training works. Such structures may incorporate geotextiles as a filter, reinforcement, and containment. Increasing the resistance might be a better solution if there is not a way to alter the flow pattern, or the comparison of costs leads to such a decision [16].

2.3.2.1. Geosynthetic containers

The main application of geotextiles in scour protection is their use as a filter below an armor layer, placed to resist hydraulic actions, but there are also geosynthetic solutions without armor or ones that provide the armor itself like geosynthetic containers.

Figure 11. Photograph of filling plant for geosynthetic containers [16]

Geosynthetic containers were created to overcome the placement problem of filters, making elements that combine the filter capacity and sufficient weight to withstand the hydraulic action. Geo-containers are multi-purpose elements as they can be manufactured according to any demand of raw material, size, shape, filtration capacity, and strength. Their size is chosen according to the hydraulic demands and operational restrictions. Consequently, it should be as large as possible since the larger it is, the lesser they are displaced.

Additionally, for safe placement and sufficient long-term resistance, the container's material must be chosen such that it will resist all mechanical loads. This choice depends on the selection between the use of geosynthetic woven or nonwoven. The first one is characterized by high tensile strength and large straining capacity, and if the containment is damaged, a woven cloth might be more susceptible to crack propagation. On the other hand, the nonwoven is characterized by a high straining capacity, so the tensile strength may be less against mechanical impact, moreover, by allowing large deformations a nonwoven will be able to withstand the impact load when hitting the ground and increase protection against abrasion.

Abrasion resistance is highly important when geotextile containers are used without armor, and sediment and bedload transport is acting. If additionally, containers are exposed to sunlight for at least some time, the fabric must show a sufficient resistance against weathering in general, including UV radiation. Today long-lasting solutions are possible as for example Groynes in Australia that did not show degradation in 10 years [16].

Figure 12. Photograph Sea Groyne with geotextile containers [16]

Some of the previous points have been demonstrated in researches dedicated to geosynthetic containers. For example, the paper [17] presents a study where a geo-container system is assessed to protect bridge abutments in alluvial channels. As a result, it exhibited that geosynthetic containers are a promising alternative to Rip-Rap systems for uses like bridge abutment-scour countermeasures and that it is necessary to connect the geo-containers to strengthen the system and avoid individual failures. Finally, geo-containers proved to be a good complement to Rip-Rap for blocking the winnowing of sediment from between bed-armor elements like Rip-Rap stone, since they can be placed more easily than underlay cloths.

As commented before, the combination of different scour protection systems ends up with a good result as they can complement between them to improve the disadvantage of any of the systems. The research [18] assessed the combination of geosynthetic containers and collars in clear water conditions, which is an interesting combination having in mind that includes one system as a flow altering device and another one as an armoring device. The research focused on the protection of four piers centered in the channel firstly with collars of different materials (steel, aluminum, and Perspex) and then only with geosynthetic containers. Later an improve solution was done using collars at the same time with geosynthetic containers filled with crushed concrete and palm shells.

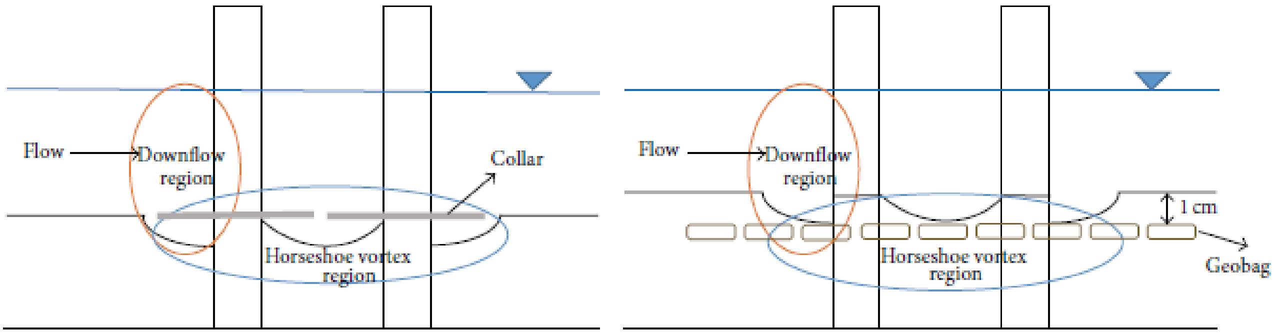


Figure 13. Scour around a pile protected by (left)collar and (right) geosynthetic container. Reference [18]

Collars were installed at the sediment bed level with an effective width three times the diameter of the pier for all experiments of collar countermeasures and with a geosynthetic container located around the piles. Experiments were developed in a 24-hour period, and all tests were conducted at the threshold of motion of the bed material, at which the maximum depth of the scour hole was expected. With collars installed at the streambed level, there was no sign of scouring or the horseshoe vortex at the upstream face of the piers at the beginning of the experiment. In contrast with unprotected piers, in all the experiments scouring started from downstream of the piers due to the action of wake vortices. Then the scour holes were extended upstream, and they undermined the collars. Crushed concrete mixed with oil palm shells has greater strength, so the bonding between the material in the oil palm shells and the crushed concrete decreased the voids and thus reduced scouring [18].

Figure 14. Photograph of aluminum collar used in reference [18]

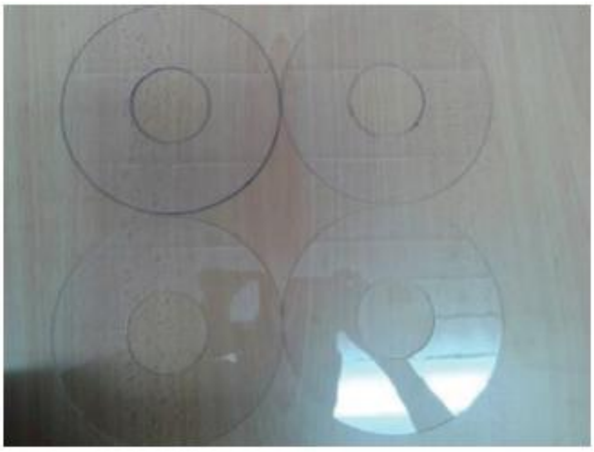


Figure 15. Photograph of Perspex collar used in reference [18]

Figure 16. Photograph of steel collar used in reference [18]

Figure 17. Photograph of geocontainers with crushed concrete containing oil pam shell used in reference [18]

The following figure shows the scour depth results between the different combinations of collars and protection, including geosynthetic containers. The most effective result achieved from the combination of countermeasures occurred when a steel collar and a geosynthetic container were used. Because steel was stiffer than the other collars, and as it helps to make it more rigid, it affected the movement of the horseshoe vortex in the front of the pile. Moreover, the pile is covered with a geo-container 10 mm below the sediment, protecting the pile from the scouring effect. The result for all three runs gradually increased, but without the countermeasures, the increase occurred much more rapidly.

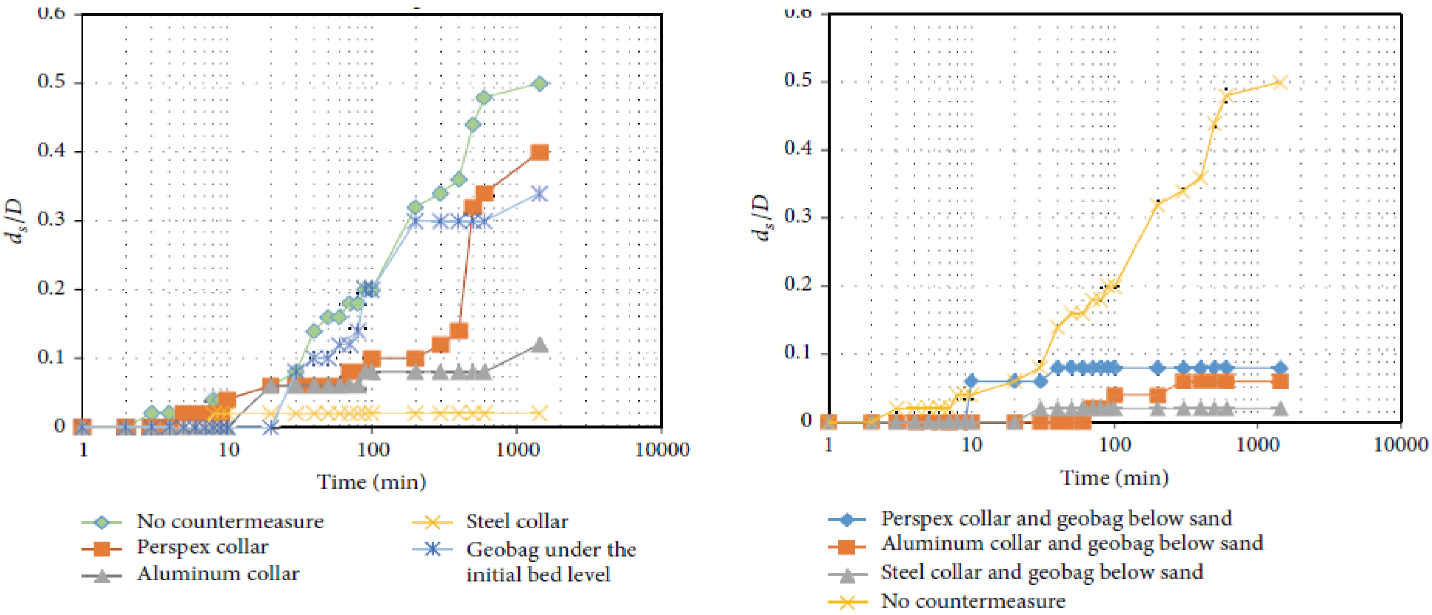


Figure 18. Dimensionless scour depth vs time for all the scenarios [18].

The scour reduction achieved for the front and rear piles caused by the independent collar and geo-container using different types of countermeasures is shown in the following table. There was a 96% reduction in the scouring of the rear pile when the combination of a steel collar and a geo-container was used, indicating that this combination was more effective at reducing scour than the other countermeasures. Scouring in the combination of a steel collar and geo-container occurred at 30 min, whereas it occurred in 8 min for the single steel collar. The better efficiency of the steel collar might be due to a weaker downflow at the upstream face of the rear pile since the steel was heavier and rigid than the other materials. The maximum scour depth was observed at the upstream face of the front pile for all tests.

#	Type of countermeasure	Scour reduction after 24h (%)
1	None	-
2	Perspex collar	20
3	Aluminum collar	76
4	Steel collar	96
5	Geocontainers	44
6	Perspex collar and geocontainers below sediment	86
7	Aluminum collar and geocontainers below sediment	88
8	Steel collar and geocontainers below sediment	96

Table 3. Scour reduction scenarios. Reference [18]

Geosynthetic containers are a good choice for any infrastructure project and have a lot of advantages concerning standard engineering solutions. Nevertheless, is important to keep in mind the improvement of the systems with better environmentally friendly practices. These practices had been studied in research in clear-water conditions by Akib, Shatirah, et al [19], and include the assessment of the use of fine and coarse crushed recycled concrete as a filler instead of sand filler in the geo-containers to promote green technologies. Various experiments were carried out to investigate the possibility they have of reducing the impact of scour in piers of a skewed integral bridge during flooding conditions.

Figure 19. Geocontainers with fine crushed concrete and coarse crushed concrete [19]

The analysis of the results of the research demonstrates that the capacity to decrease the scour depth is not affected, and the trend of protection is conserved as normal in geo-containers, wherein the low velocity is more effective in decreasing the scour depth and as the velocity increase the effectiveness decrease. During the experiment, it was recognized that the finer the mixture of crushed concrete the more flexible it behaves, while the coarse crushed recycled concrete produces a slower scour rate. However, this crushed concrete was crushed from recycled concrete, promoting an environmentally friendly, economical, and yet effective solution to the design of scour protection. Furthermore, it could benefit the economic sectors given that wastes are turned into something useful.

2.3.2.2. Armed soil by geotextile

It is a more usual and cost-effective strategy to strengthen the bed against the hydrodynamic loads due to the presence of the pier in the flow with multiple existing systems. Among methods that can be appropriate to decrease and control local scour of bridge piers directly is possible to find the ones described previously, Rip-Rap, collar, wire gabion, and geo-containers. Separately from these methods, some new research [20] explore the effect of geotextile layers in decreasing the local scour depth of a cylindrical single pier in clear water conditions.

The experiment includes ten runs with a critical velocity ratio (u/uc) of 0.93 and a duration of 56 hours. The sizes of these geotextile layers were based on the patterns suggested by the Rip-Rap research by Gales RR (1938) [21], Bonasoundas M (1973) [22], and Neil CR (1973) [23]. The following table resumes the tests, including the sizes of the layer, the scour hole size, and the development of the scour depth in time. It is important to clarify that in all the protected tests the scour depth corresponds to the deepest depth achieved in the scour hole and not the scour depth in front of the pier as was observed in other research studies.

As seen in the test 1, a change in scour depth after 8 hours is very small. Also, maximum scour depth in the front of the pier was 11.9 cm which is approximately 2.6 times as much as the pier diameter. Ghorbani, B., and J. A. Kells (2008) [29] deduced that more than 70 % of scour occurs in the first 7 h of the test. In this case more than 75 % of the scour occurs in the first 8 h.

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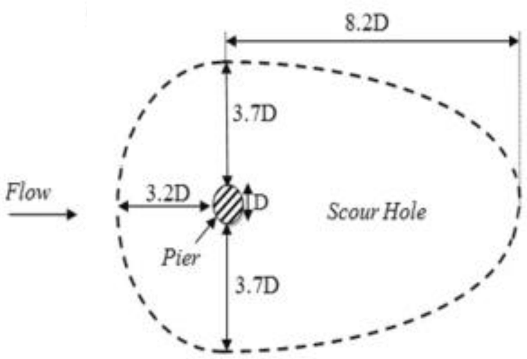
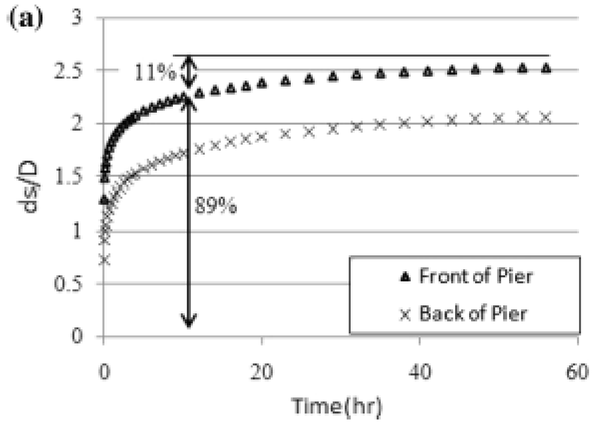
<tr><td>1</td><td>
</td><td>
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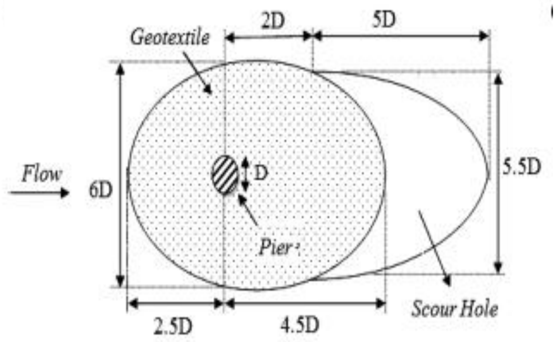
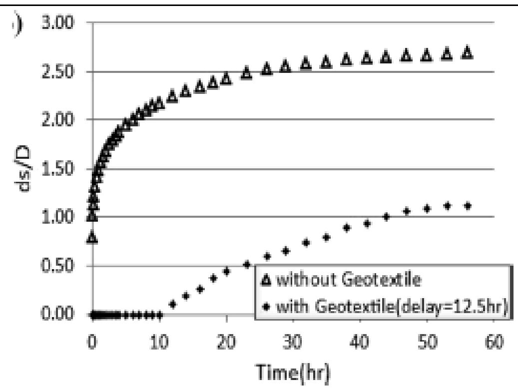
<tr><td>2</td><td>
</td><td>
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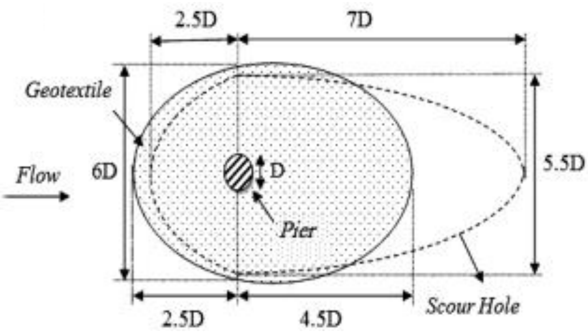
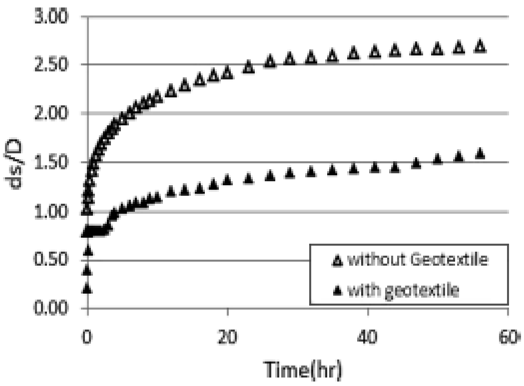
<tr><td>3</td><td>
</td><td>
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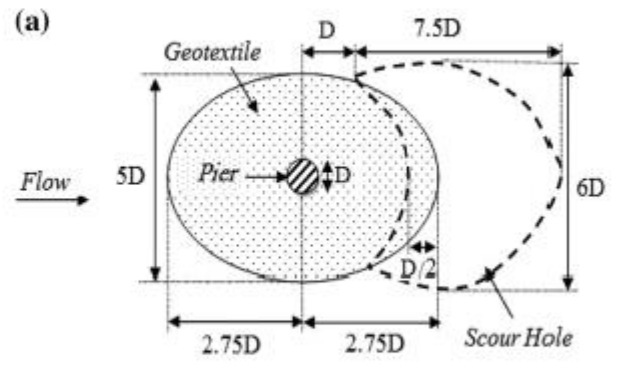
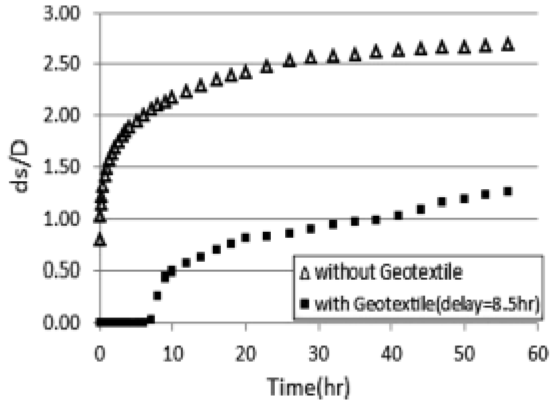
<tr><td>4</td><td>
</td><td>
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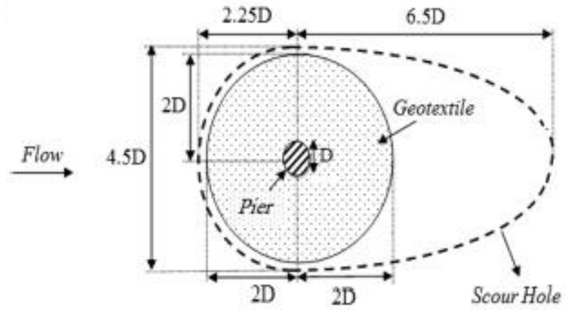
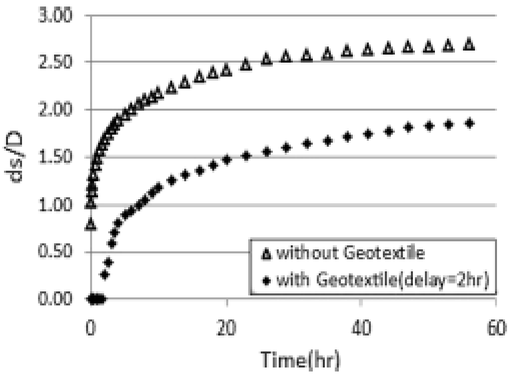
<tr><td>5</td><td>
</td><td>
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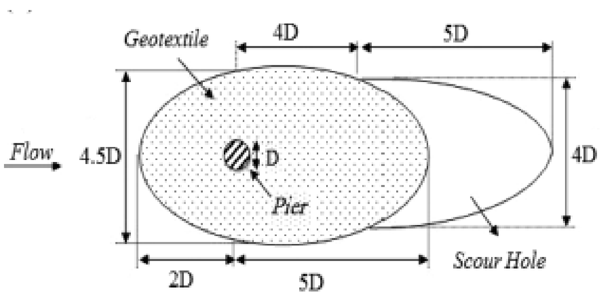
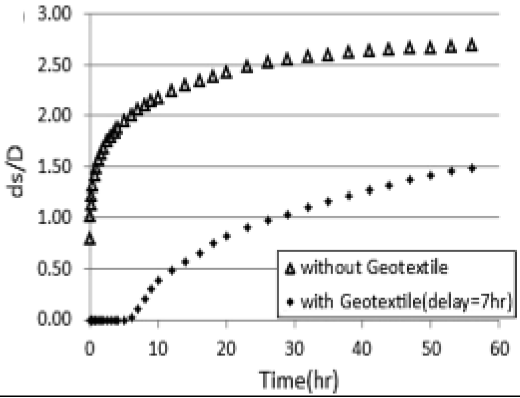
<tr><td>6</td><td>
</td><td>
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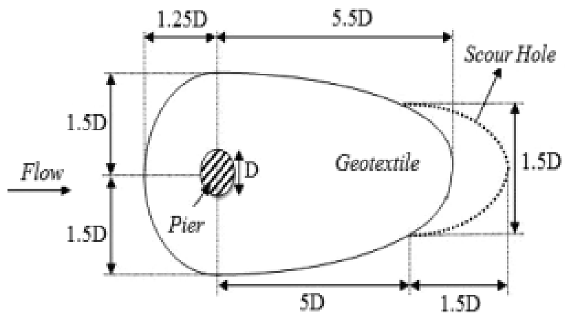
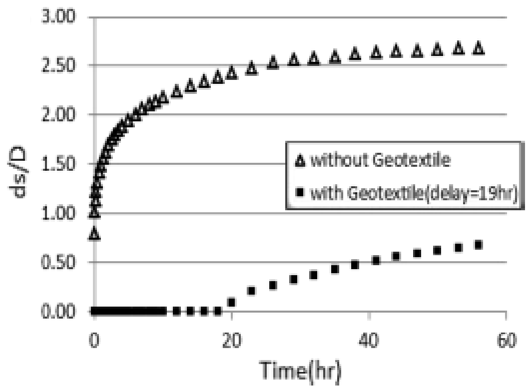
<tr><td>7</td><td>
</td><td>
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Figure 20. Geotextile layer sizes and scour holes in reference [20]

It is significant to highlight that test numbers 2, 4 and 5 represent the experiments in which the geotextile layer had a size based on the studies previously referenced (Gales RR (1938) [21], Bonasoundas M (1973) [22], and Neil CR (1973) [23]). Test number 3 corresponds to the same geotextile layer of test number 2, but the placement of the layer is 0.8D (D is the diameter of the pier), equivalent to 4 cm under the initial bed. The research only shows 1 test with this condition even though was done for the other references. All tests report similar behavior, each one showing a high scour rate until the level of the geotextile layer, and after arriving at this level, the scour rate decrease as can be seen in the scour depth vs time graph in which the delay is cero compared with all the other tests. On the other hand, all the other tests were done with only a 2 mm cover.

Furthermore, during all the other tests no scour occurred in front and at the sides of the pier, which led them to focus on decreasing the scour hole extended around. Test numbers 6 and 7 represent the optimization process based on trial and error where the size of the geotextile layer is optimized in terms of efficiency in reducing the scour hole. Consequently, the geotextile layer of test number 7 decreased the scour depth and transferred the scour location 5.5 D (D-pier diameter) downstream. The geotextile demonstrates to reinforces the scour protection through the strengthening of the bed and change in the flow pattern.

The following figure resumes the results of all the scour depth in time and underlines the suggested pattern as the best arrangement, with a delay of 19 hours until the first signs of scour in downstream edges. Moreover, a second conclusion can be drawn for the circular pattern, since they turned to be less suitable for the coverage system due to the intensity of the vortex behind the pier. The circular layer of geotextile has an application like the collar system and a comparison of its performance is suggested for further studies.

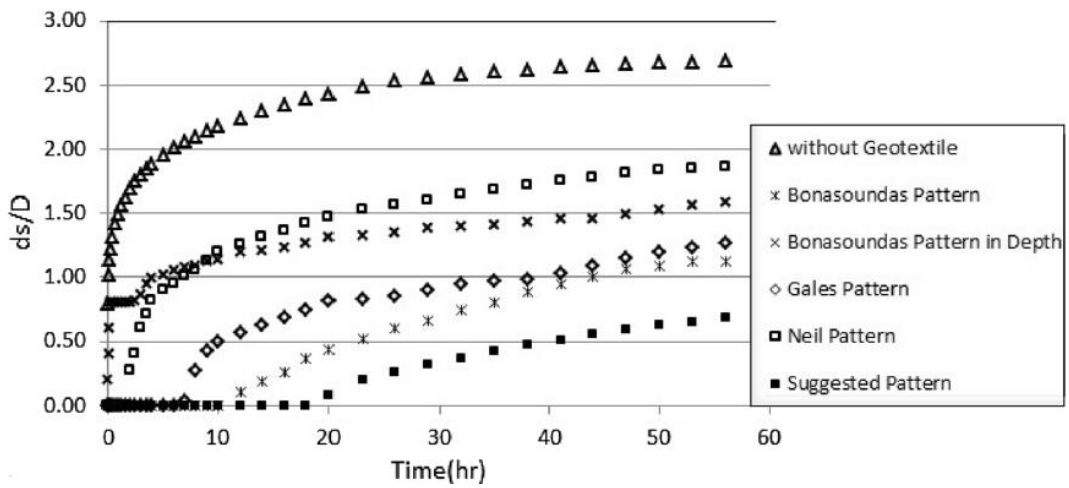


Figure 21. Scour depth vs time-geotextile layer system. Reference [20]

2.3.2.3. Others

There are other systems that even if not used often to protect piers or have not been studied enough to be applied in cases out of experimental facilities, should be highlighted given their advantages in the contribution to the pile scour protection. Among these systems, are found geosynthetics like mattresses, tubes, and geotextile mattresses with sloping curtains.

Mattresses can form continuous layers, usually filled with concrete or mortar. Theoretically, also sand-filled mattresses can be used as is done for landfill protection, but not much research has been done in this field. Mattresses can be placed “endlessly” since their fabrication is sewn together as needed and then sections of the mattress are filled in place. To achieve certain flexibility and permeability, mattresses consisting of columns and rows of ''pillows'' are used. The seams between the concrete-filled pillows provide some permeability of the layer if needed, and the flexibility desired for good adjustment to deformations of the subsoil [16].

The placement of these systems underwater in a conventional way is difficult since the geotextile will float before being filled. Therefore, for applications, underwater prefabricated mattresses are used and are placed by special cranes. Due to the difficulties in the underwater installations, this system usually is not considered to protect piles and is more frequently used for coastal protection. Nevertheless, geosynthetic mattresses have the advantage of being more durable solutions and more environmentally in comparison with conventional solutions, which gives space to the discussion to devote more research to this system as a pile scours countermeasure.

Secondly, geosynthetic tubes are elements that can be manufactured and used as protection in linear structures as channels. These tubes are often used in scour protection as toe-protection of riverbanks and coastal dikes, as the core of levees, and longitudinal dikes. For these applications, the geosynthetics tubes are filled hydraulically with sand or with mortar. Sand-filled tubes provide greater flexibility than mortar. However, as in the case of mattresses, they can be used for bed protection, and in deep detail bed protection around piers, always including the help of another geotextile as a filter to avoid excess pressure below the tubes.

Finally, a geotextile mattress with sloping curtains or plates is a new system that is still not used as an alternative in a real case study, but some research has been done with promising results to evaluate further uses of it, for example in pile scour protection. This system is composed of a geotextile mattress, sloping curtain pipe, sand pass openings, and reinforced belts, as shown in figure 22. It works principally as a tool for disrupting the flow and lowering the shear forces over the bed.

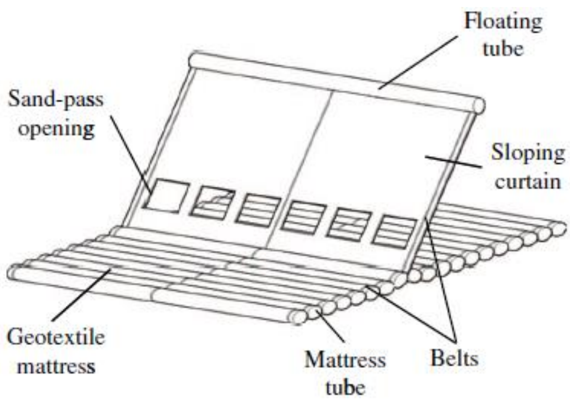


Figure 22. Geotextile mattress with sloping curtains [24]

When approaching the sloping curtain, the near-bottom flow is divided into two parts. The upper part is guided upward by the sloping curtain and turns downward after climbing over the curtain, whereas the lower part goes directly through the openings near the bottom of the sloping curtain with a high concentration of sediment, colliding with the upper part at the downstream side of the curtain. The collision between the two parts of the flow forms two vortices: a top vortex near the top edge of the curtain and a bottom vortex close to the bed. The bottom vortex provides a long low-velocity zone on the other side of the curtain that is safe from scour. Therefore, the bed or bank in this zone is protected from erosion, as figure 23 shows [24].

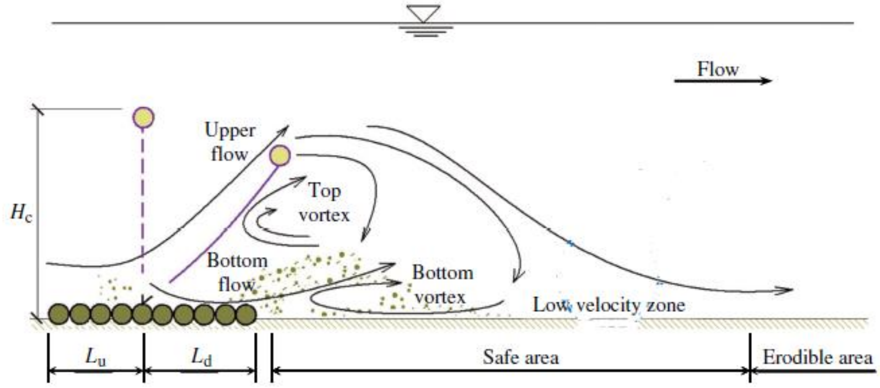


Figure 23. Flow field of the geotextile mattress with sloping curtains [24]

As commented before, the achievement of the safe zone can be resourceful for the protection of multiple structures. For example, in the case of pipelines, research like reference [24] showed it achieved a significant result. Moreover, other studies had shown that this device can help significantly in the stability of sand beds. The reference [28] did a numerical analysis concluding that mattress curtain sets can form sand dunes downstream of the curtain structure and allow a long section of sand bed landform to be maintained steady. Likewise, this kind of structure can improve the flow structure close to the sand beds and form a long safe zone with a lower speed than the critical shear velocity.

The research of this structure as a scour pile countermeasure should be fostered even though the system does not directly avoid the formation of the vortex, but the structure can deliver a flow that can create a less powerful vortex and overuse the bed motion in favor to possibly refill the scour hole. However, further research should be done to guarantee these hypotheses.

3. Laboratory description

The experimental work reported here is performed in the Hydraulic Lab G.Fantoli that is located in the 4A Building at the Leonardo Campus of the Politecnico di Milano (Milano, Italy).

3.1. Experimental facilities

The experiments were performed using a transparent flume with rectangular section. Dimensions of the channel were: length of 5.8 m, width of 0.40 m and height of 0.16 m. The channel sides were connected to the channel cover by steel bolts, as shown in Figure 24.

Figure 24. Experimental flume

These experimental facilities can reproduce the live-bed scour condition and the clear-water condition. In the present study the top panels of the flume were detached to work as a free surface flow. The flow in this flume is supplied from a tank located upstream the channel that is connected to an underground storage tank that through a submerged pump keep a continuous flow of water. The flowrate was measured with an electromagnetic flowmeter installed on the supply pipe to the tank.

Additionally, a water recirculating system has been installed in the facilities to guarantee the constant discharge of water in the channel for the time needed in any test. The channel has a cylindrical pier located in the channel axis at 450 cm from the inlet. The outer part of the pier was a PVC pipe with internal and external diameters of 0.06 m and 0.064 m, respectively. The inner part was a Plexiglas cylindrical bar that could slide within the outer one and can be lifted to simulate the presence of piles on the channel and assess the behavior of the sediments around it [25].

Depending on the selected scour condition, the configuration and accessories of the experimental facilities are changed or detached. In the case of the clear-water condition, the channel only requires a series of sticks as a boundary condition at the end of the channel to control the water depth, and the measures of the bed level were made with a gauge supported on transversal support that references the distance of the measures in terms of the width of the channel.

Figure 25. Point gauge

Figure 26. Photograph of sticks as a boundary condition at the end of the channel

Before any test is done in the experimental facilities there is a tool shown in Figure 27 that is used to straighten the bed and have an initial bed as uniform as possible to run the test and observe any significant change. Furthermore, should be highlighted that in addition another procedure is done before the beginning of each test, where some water is sprayed manually over the sediments to avoid lift sediments when the channel is filling.

Figure 27. Device to straighten the bed

The following figure represent a sketch for configuration of all components which are installed in the facilities for clear water and live bed condition.

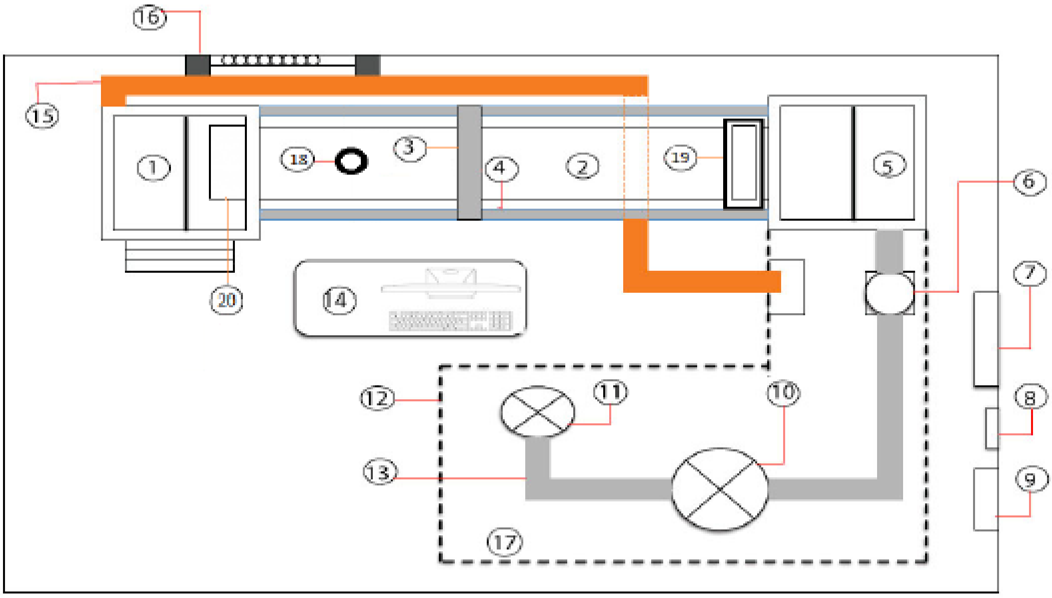


Figure 28. Experiment facilities plan. Reference [26]

1. The outlet Tank
2. A rectangular duct(channel)
3. Transverse positioning system
4. Longitudinal positioning system(roller)
5. The inlet Tank
6. Magnetic flow meter device
7. Hopper operator and time controller
8. Magnetic flow meter reader
9. Electric power controller
10. Main-stream Valve
11. By-pass Valve
12. Pumping and water discharge control unit.
13. Inlet-Pipe
14. Desktop-PC
15. Outlet Plastic pipe to recirculate water
16. Gauges and piezometers (aren’t used in the present study)
17. Underground Water Storage
18. Cylindrical Pier.
19. Hopper for sediment feeding.
20. Sediment’s trap basket/sticks as boundary condition.

3.2. Experimental campaign

Firstly, the evaluated system in this study is new and there is no literature or previous experiences related to this kind of system for scour protection. It was required to run initial tests with a first proposal of the net named "geo-carpet" in the present study. Further information on the functioning of the system and details will be done in the chapter of analysis of the experiments.

Two tests were performed with the first proposal of the geo-carpet to check possible problems in the performance, installation, and material behavior of the scour protection system in the channel. Both tests were done with a discharge of 8.6 l/s and a duration of 4 hours. The discharge flow was selected having in mind the definition proposed by Radice and Ballio (2008) [27], in which the incipient motion corresponds to a dimensionless sediment transport rate per unit width. Thanks to this definition and an experimental test that measures the motion of the sediment at different flow discharges were possible to define the discharge value to use in the experimental campaign.

The graph in the Figure 29 represents the results of this experimental test in which in two points of the channel the number of particles in motion was measured and with the mean values between them and a lineal interpolation the discharge value for the experimental campaign was selected.

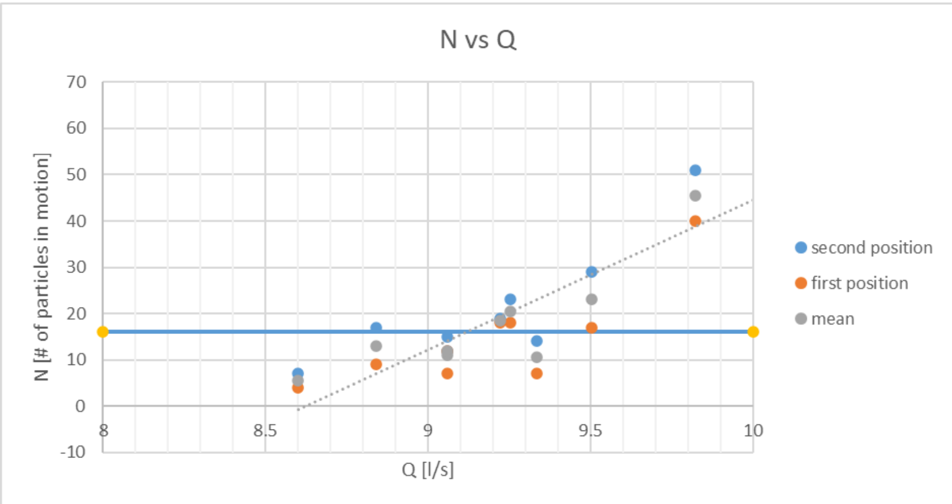


Figure 29. Results experimental test of sediment motion at different flow discharges

The first test was done without any scour protection to have a reference value of scouring volume, while the second was done with the scour protection system installed. The first proposed "geo-carpet" system consists of a net with dimensions of 46 cm in length and 40 cm in width, which is the same width as the channel in this case. The size of the mesh in the net was 1.5 mm and was formed by two pieces installed together in the channel to cover all the area around the pier, as shown in Figure 30 and 31 the installed net with the sketch of the two pieces dimensions.


Figure 30. Photograph prototype net countermeasure

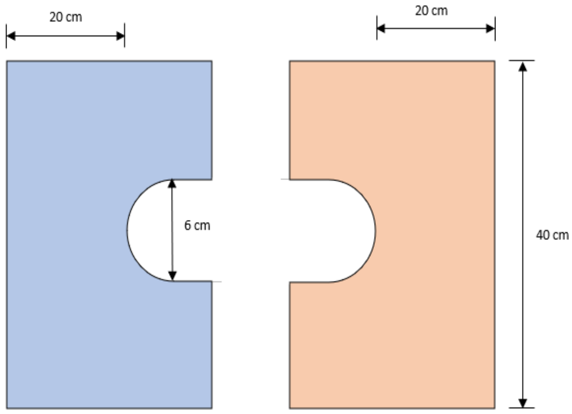


Figure 31. Detailed sketch prototype net

These initial tests help to set a higher time duration, a better material choice, and more importantly, a change from the two pieces arrangement to a one-piece arrangement with the same dimensions and with the hole for the placement of the cylindrical pier in the middle. Further benefits of the one-piece arrangement are discarding the weakness of the connection in the two pieces arrangement and allowing that the assessment of the variation in the parameter of the covered area was easier to study.

Moreover, to ensure the confinement of the net and the correct performance in the installation of the net some blocks were used to keep it always in contact with the sediment. In this way, the interaction between the sediments and the net can be guaranteed as expected. Figure 32 shows for test 1-S the use of four blocks to fulfill this task and after the installation were removed.

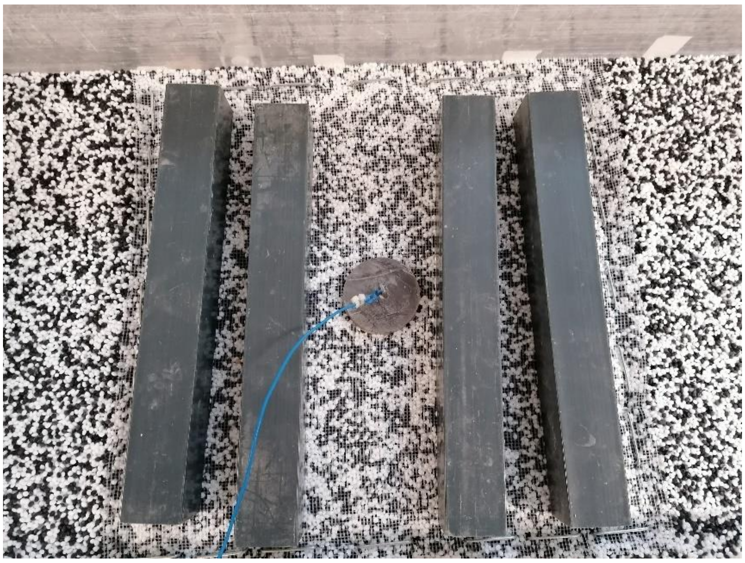


Figure 32. Photograph installation of the net

The sediment used in this work was made of Polybutylene Terephthalate (PBT). Uniform, quasi spherical particles with an aspect ratio of 2 were used. Three samples of sediment have been mixed to have enough to perform the experiment based on their properties' similarity. The Sediment density was ρ_s= 1,317 kg/m3 and Porosity= 0.41 [26]. The next table show the equivalent diameter and particle diversity indicator for each sample:

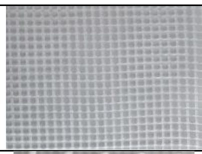
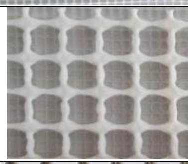
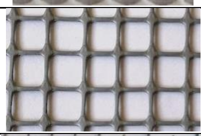
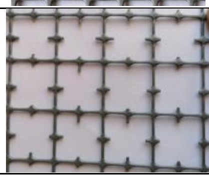
Where:
d16- sediment size for which 16% by weight of the material is finer (mm).
d50- sediment size for which 50% by weight of the material is finer (mm).
d84- sediment size for which 84% by weight of the material is finer (mm).
σ_g - the geometric standard deviation.

	Sample #1	Sample #2	Sample #3
d16 (mm)	3.18	3.17	3.26
d50 (mm)	3.29	3.3	3.35
d84 (mm)	3.37	3.37	3.52
σ_g	1.029	1.032	1.039

Table 4. Sediment properties

As commented on the objectives of this study, one of the goals to achieve is the assessment of the use of a geo-carpet as a pile scours countermeasure in clear water conditions. For this assessment, an experimental campaign had been done with multiple tests to evaluate the behavior of some parameters in the performance of the proposed countermeasure, the test includes the variation of the protected area and mesh size of the net.

The campaign includes the use of 4 different mesh sizes: 2 mm, 7mm, 12mm, and 24 mm. The material related to each size is different given that each net is prefabricated, thus, the influencing factor to decide between multiple materials that were ideal to do the test was the mesh size. The mesh size 12 mm and the one size 24 mm are made by the same material because the mesh of 24 mm was made from the same net of 12 mm manually. For the codification of the test, the mesh size is related to the following letters:

2 mm	S	
7 mm	M	
12 mm	L	
24 mm	XL	

In addition, the campaign is composed by four different configurations of covered area in which the first 3 have the same 40 cm of width but different protection in the area upstream the pier. For example, configuration 1 protects only until 20 cm upstream of the pier location, configuration 2 protects only until 10 cm upstream of the pier, and configuration 3 protects only 5 cm upstream of the pier. The distance mentioned before refers to the upstream face of the pier. Configuration 4 have different covered area upstream and downstream of the pier; upstream the pier the protected area is only 5cm and downstream is 56 cm giving as final dimensions 67 cm length and 40 cm width.

Configuration 4 has a different protected area as a consequence of the optimization process in the formation of the experimental campaign, in which through the results of the first tests, the next test was oriented to obtain more meaningful results and values. For instance, the dimension of configuration 4 was a result of the initial test that led to the creation of the fourth configuration. Besides, this optimization approach has the benefit of decreasing the number of tests since some tests could be perceived as less meaningful than others.

The system requires a mechanism to keep the net in place and avoid the water moving it for which were implemented stainless-steel nails in form of "U" with the dimensions shown in Figure 34. These were used in the perimeter of the net, inserting them into the sediment to keep the net in place during all the tests. The nails can be seen in the photos presented in figure 35 to 43. Only in the case of the mesh size M, it requires using it near the pier area (Figure 33) to avoid the floating effect of the material, being the only one that presents the inconvenience.

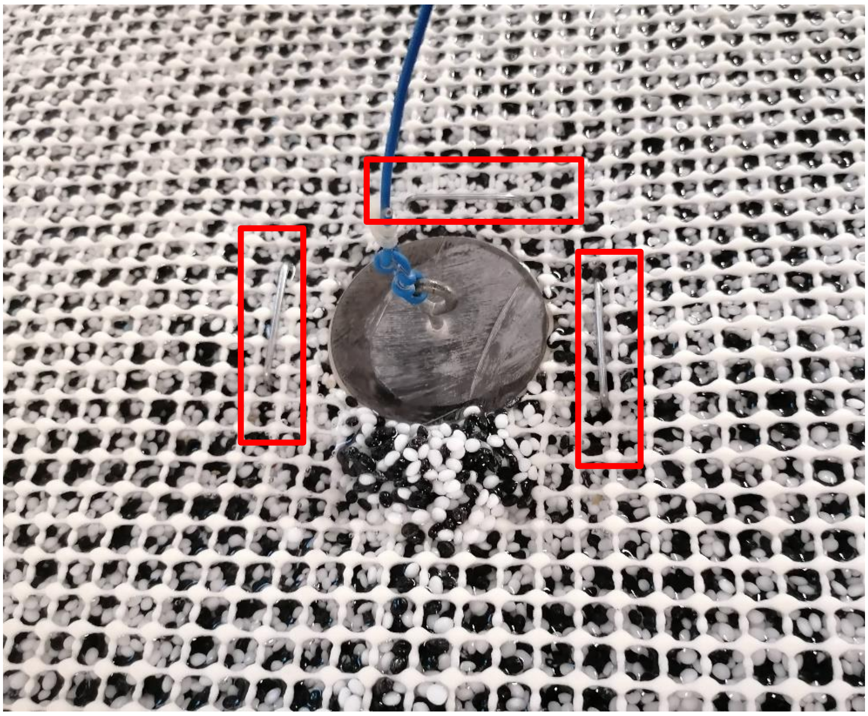


Figure 33. Photograph nails placement test 1-M

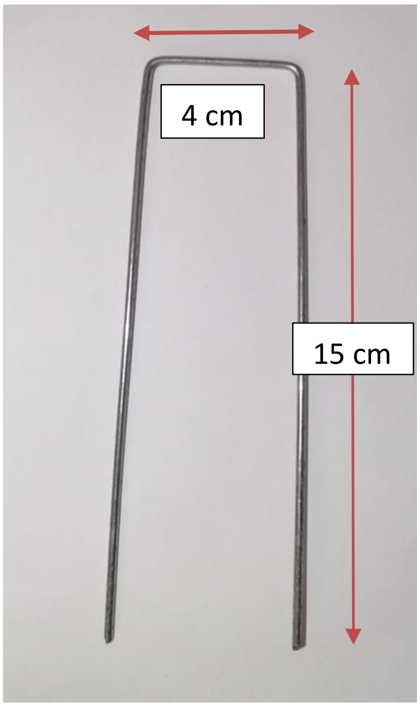
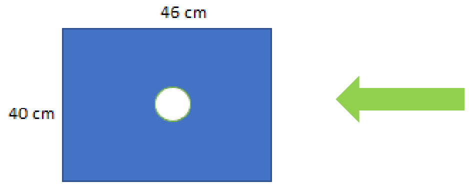
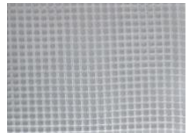
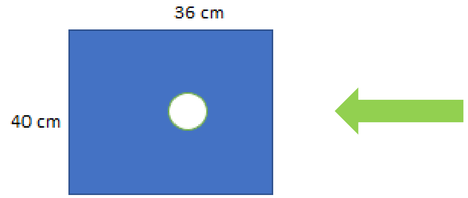
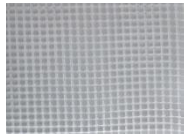
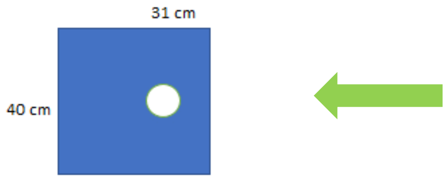
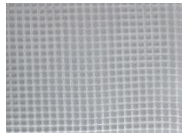
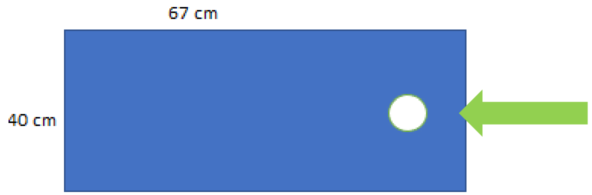
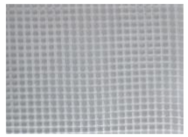
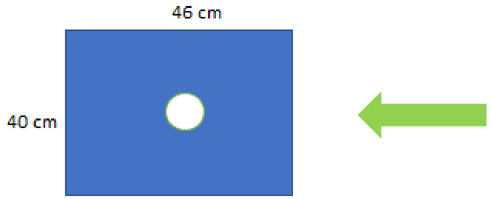
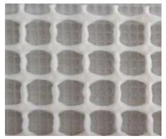


Figure 34. Stainless-steel nails

At the end of each one of the tests was measured the accumulated and eroded volume, which will be analyzed later. This volume measurement was done with the point gauge available in the experimental facilities, which is used to take transversal sections at different lengths of the channel to collect enough sections to recreate the surface and obtain the approximate volumes.

The experimental campaign is resumed in the following table, where a codification to identify the test in terms of the protected area and mesh size was assembled. The codification is conformed first by a number that identifies the configuration type and then is followed by a letter referencing the kind of mesh size, as commented before. This codification will be used later in a more detailed analysis of the results.

Test	Code	Discharge [L/s]	Net	Time	Mesh size [mm]	Material	Observations
1	-	8.6	UNPROTECTED	6 hours	-	none	
2	1-S	8.6		6 hours	2		complete net made in 1 piece the net cover until 20 cm upstream the pier
3	2-S	8.6		6 hours	2		the net cover until 10 cm upstream the pier
4	3-S	8.6		6 hours	2		the net cover until 5 cm upstream the pier
5	4-S	8.6		6 hours	2		the net cover until 5 cm upstream the pier
6	1-M	8.6		6 hours	7		the net cover until 20 cm upstream the pier

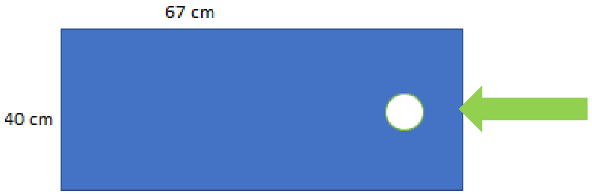
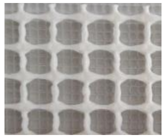
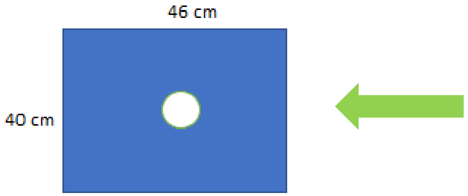
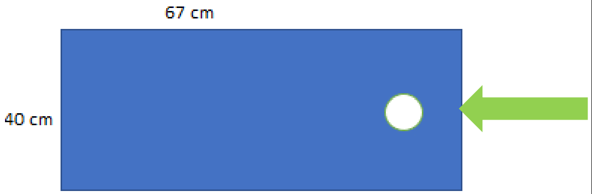
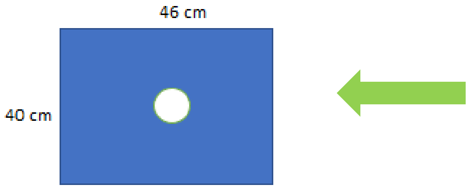
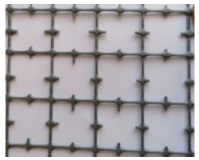
Test	Code	Discharge [L/s]	Net	Time	Mesh size [mm]	Material	Observations
7	4-M	8.6		6 hours	7		the net cover until 5 cm upstream the pier
8	1-L	8.6		6 hours	12		the net cover until 20 cm upstream the pier
9	4-L	8.6		6 hours	12		the net cover until 5 cm upstream the pier
10	1-XL	8.6		6 hours	24		the net cover until 20 cm upstream the pier

Table 5. Resume experimental campaign for clear water condition

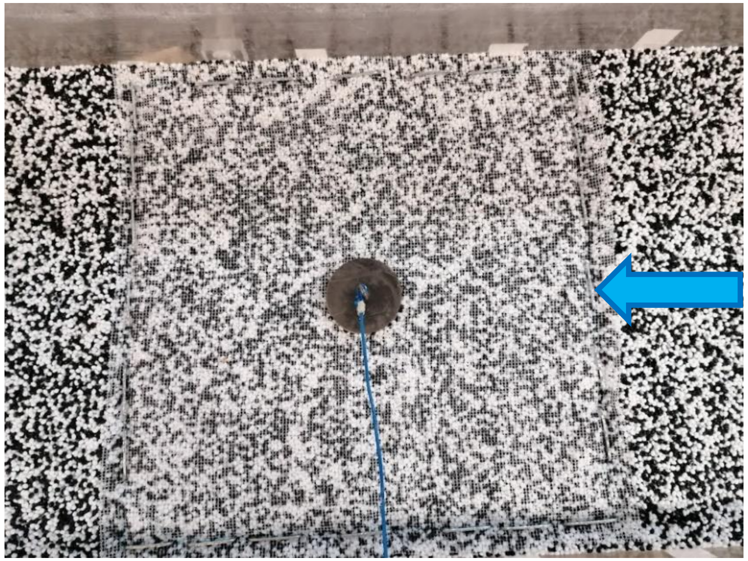


Figure 35. Photograph test 1-S

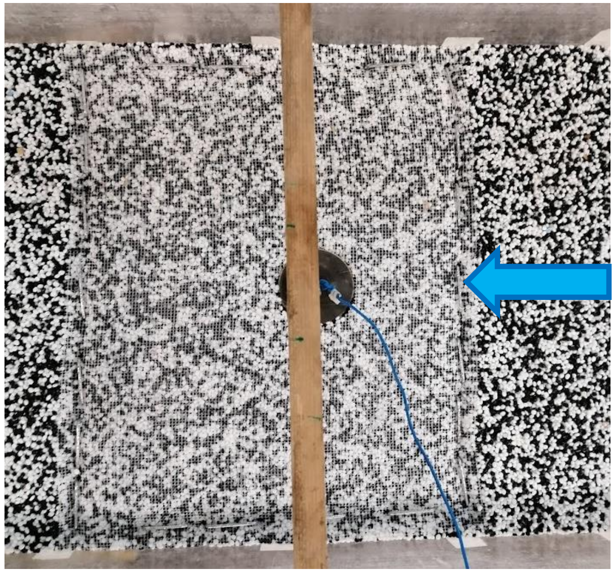


Figure 36. Photograph test 2-S

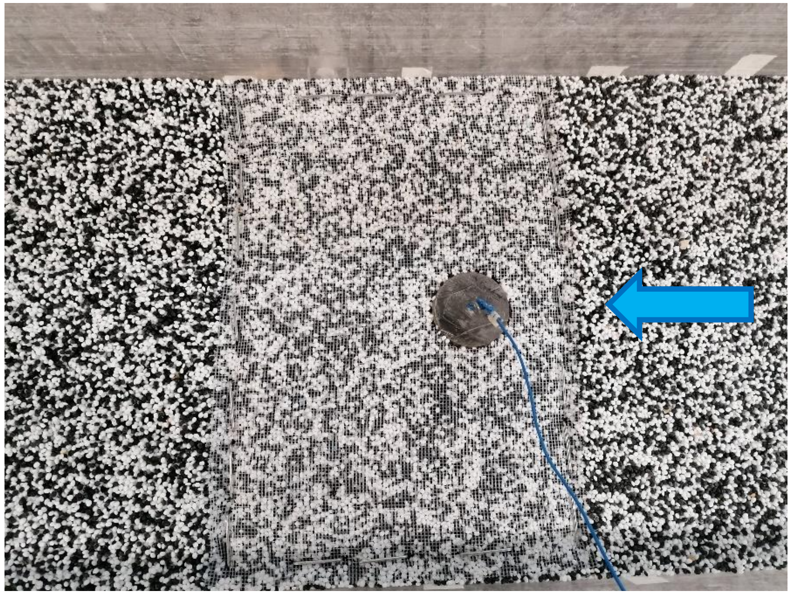


Figure 37. Photograph test 3-S

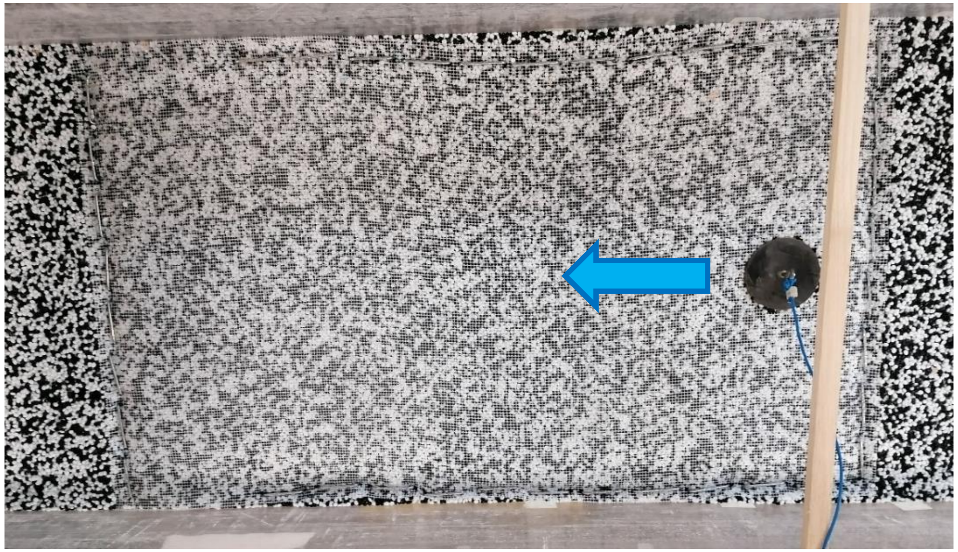


Figure 38. Photograph test 4-S

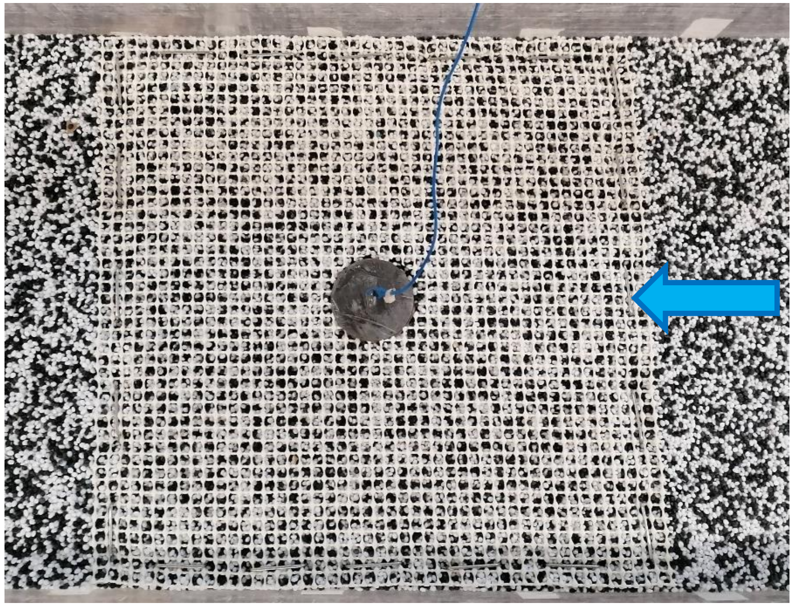


Figure 39. Photograph test 1-M

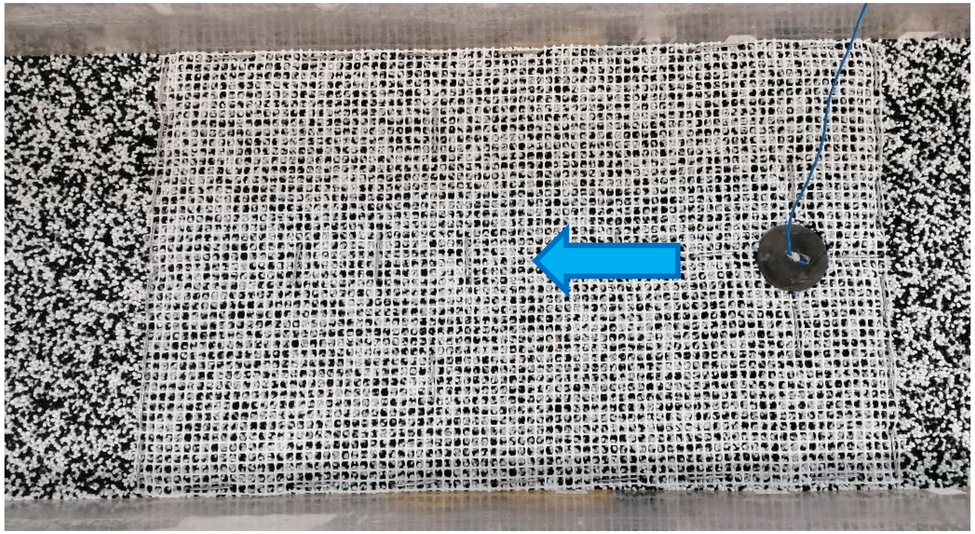


Figure 40. Photograph test 4-M

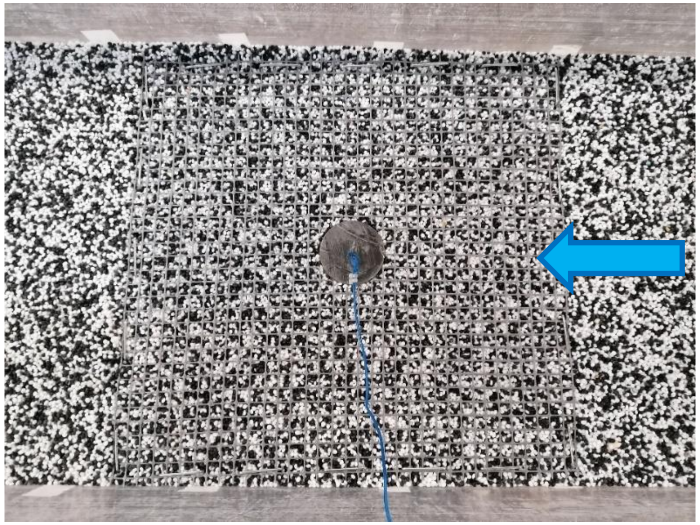


Figure 41. Photograph test 1-L

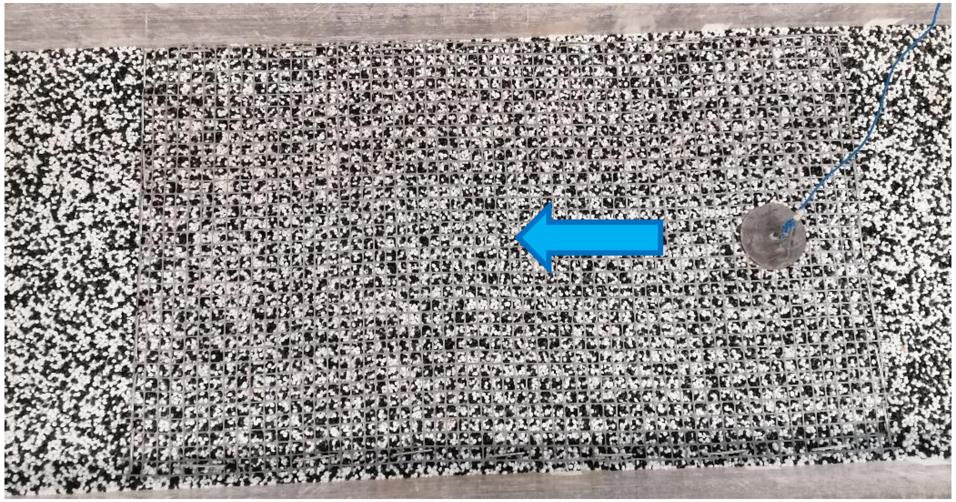


Figure 43. Photograph test 4-L

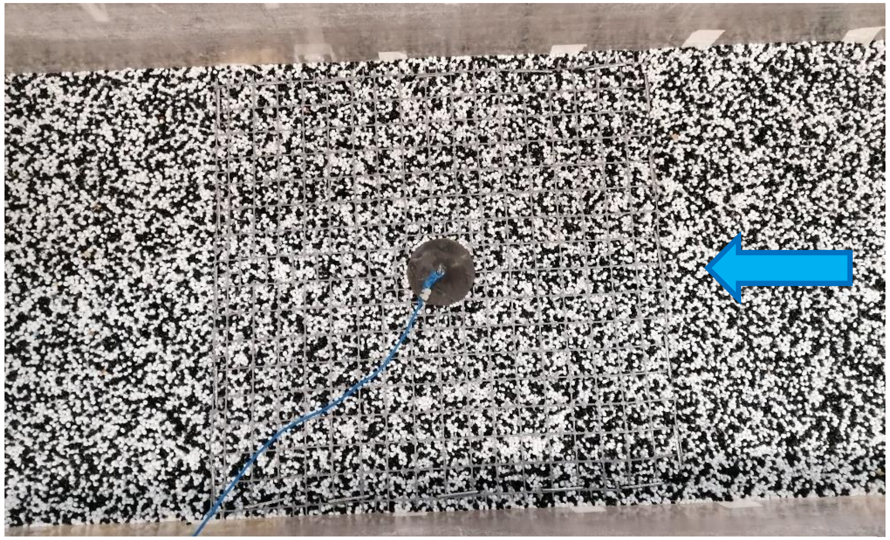


Figure 42. Photograph test 1-XL

4. Scour protection experiments and analysis

4.1. Proposed countermeasure system.

As it was described before the proposed geo-carpet system is composed by a net place over the sediments and hold through some nails. This system was assessed through the variation of two principal variables. The first one is the variable mesh size, chosen to analyze the variation in the system performance when a net have a small mesh size creating a system that is impermeable to the sediments and permeable to the water. However, as the mesh size increases, it changes the system to a condition in which works permeable for sediments and water. Moreover, this parameter gives the option to create an easy way to compare behaviors in terms of the sediment mean size, in this way even if the system is used in other sediments, it will be easier to compare the behavior as permeable or impermeable. Further details are discussed with the results.

The variation of the protected area was the second parameter chosen to analyze the change in the performance of the protection system. This variation was done easily in the first 3 configurations changing the protected area upstream the pier as it is one of the more vulnerable and where the most important interaction occurs. Nevertheless, the fourth configuration does not follow the variation trend of the others as this configuration is an optimized solution in terms of the results of the test of the previous configurations. Further details are discussed with the results.

4.2. Test results and analysis

The results of the present studies focused on the level of protection that the proposed system can induce against scour in piles. The level of protection was assessed in terms of two quantities, the scour volume and scour depth, that allow measuring the effectiveness of the system. Here are presented the results of each test for these two parameters and their relationship with the change in the variable protected area and mesh size.

The assessment of the performance of each test was done comparing the outcomes against the unprotected test, which reported a total scour volume of 3033.77 cm3 and a depth scour of 9.1 cm. The influence area of the scour hole was 892.51 cm2 as can be seen in Figure 44. This scheme represents the top view of the unprotected test showing in detail the scour depth distribution through contour lines.

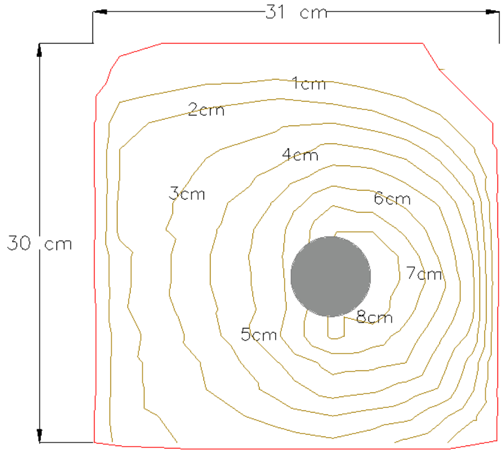


Figure 44. Top view scheme unprotected test

Figure 45. Photograph survey process unprotected test

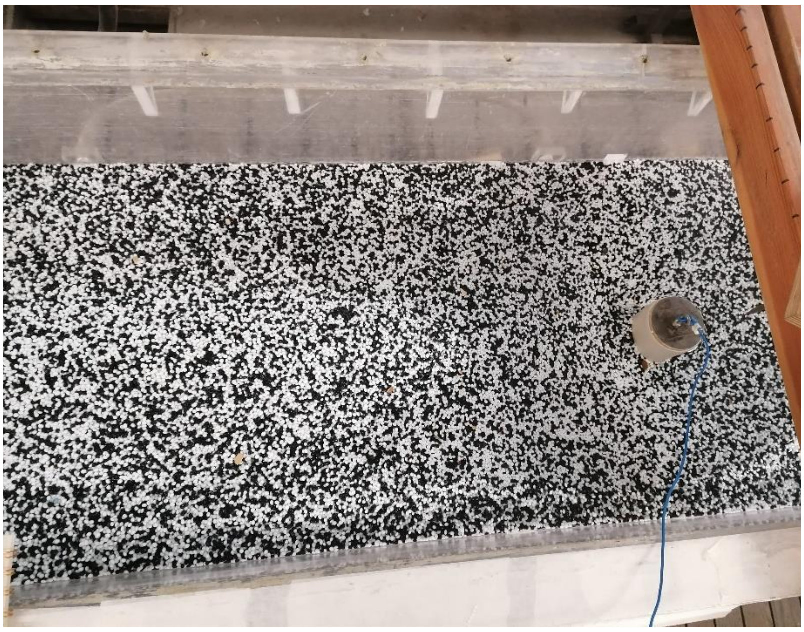


Figure 46. Photograph top view unprotected test

The outcomes of the first tests bring an initial conclusion for tests with mesh sizes S and M. The scour zone presented in the test was developed downstream after the end of the net and preserve low scour volumes in the zone where the net was installed. This singularity led to creating an analysis more detailed of the scour volume. Thus, the scour volume was analyzed between two meaningful volumes, the first one is the analysis of the scour volume just upstream of the pier since this measure shows the effectiveness of the net as a countermeasure of the zone with higher scour depth and high scour volume, moreover, these determine area makes easier the comparison between the unprotected test and the other tests.

The second analysis of the scour volume was done with a total scour volume that is not limited to a precise area and is controlled to the extension of the scour area produced in each test. Consequently, tests with similar conditions produced similar scour zones, but other mesh sizes create different scour areas. Thereby, the survey to collect the data of all the scour surfaces was done in different sections according to the most favorable positions to acquire the best data of the scour surface. For example, Figure 47 shows the two-scour volume analyzed in test 3-S in red.

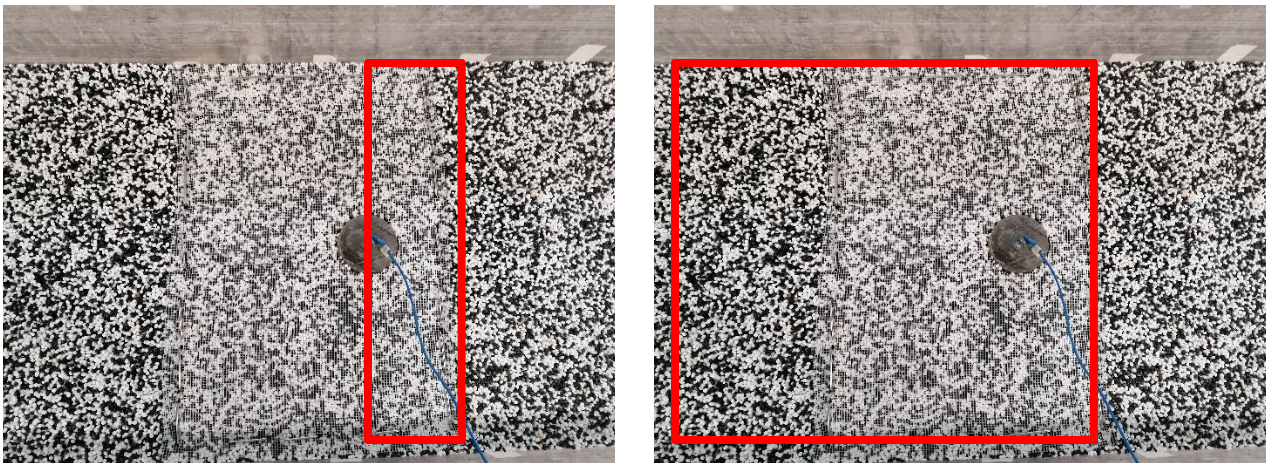


Figure 47. Scour volume areas of analysis

As considered previously, the initial test with mesh size S and M where the scour zone presented was developed downstream after the end of the net and preserves low scour volumes in the zone where the net was installed. This circumstance creates the origin of configuration 4 with a protected area in which is proposed a length downstream the pier significantly larger than the other configurations with the intention to protect the bed as well after the net area.

The following graph shows the total scour value at the end of the different tests. The values show different trends in terms of the variable that is evaluated. Firstly, in terms of mesh size, the results were not significantly different in volume but should be highlighted that the difference among them is visible in the position and extension of the scour hole. This difference can be seen in the resume table of the scour surface for each test. Secondly, in terms of variation of the protected area, there is a representative variation in configuration 4, which is coherent because this arrangement is an optimized solution proposed after the outcome of the test 1-S,2-S, 3-S, and 1-M.

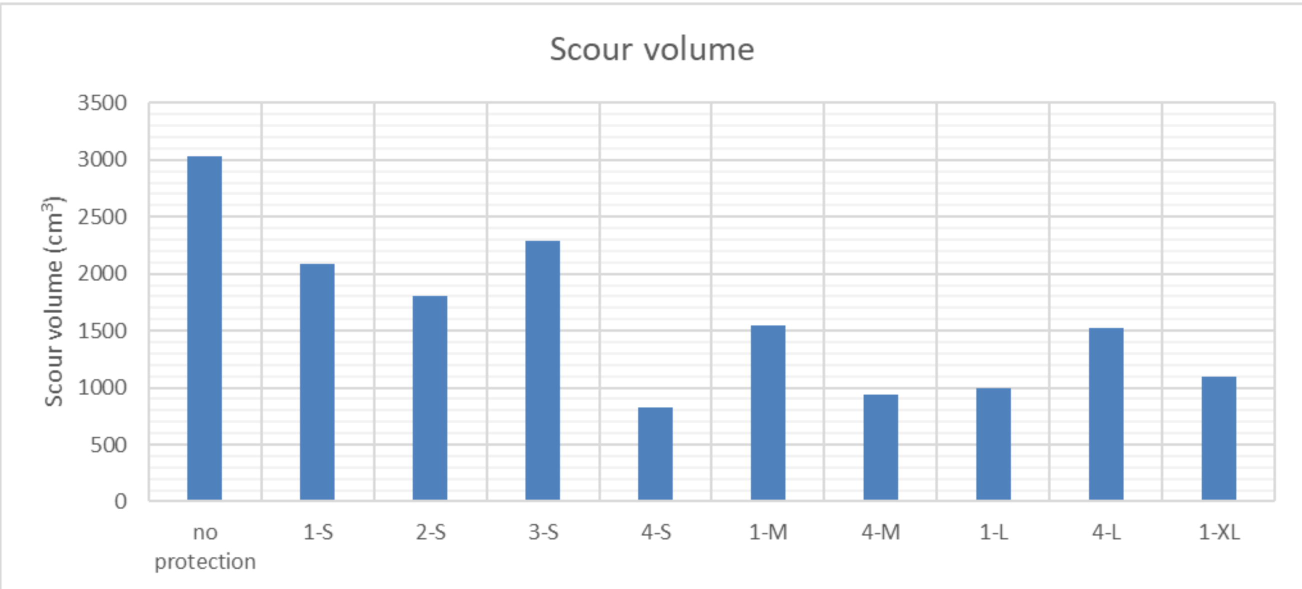


Figure 48. Total scour volume

Afterward is analyzed the scour volume presented in the upstream area of the pier at the end of each test. The registered values for the mesh sizes related to S and M show a high reduction of the scour volume, while the mesh size L and XL have higher volumes but are still lower than the unprotected test. Moreover, table 6 expresses the percentage reduction of each test compared with the unprotected value.

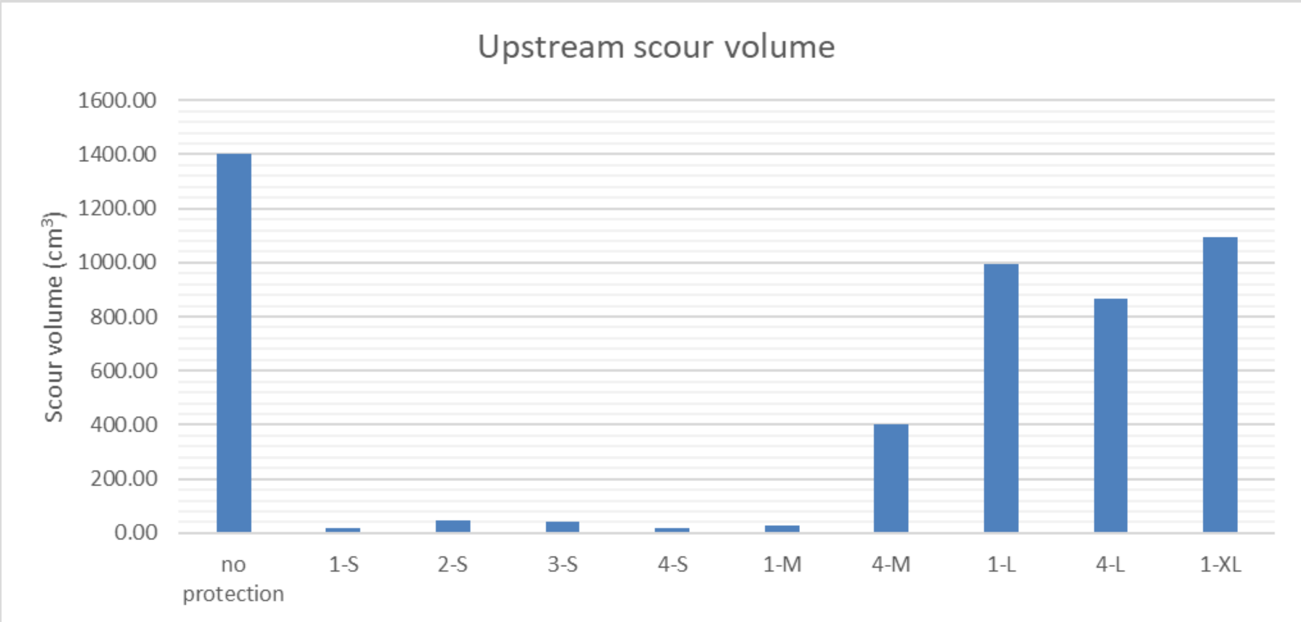


Figure 49. Upstream scour volume

	total scour volume		**upstream scour volume**	
Experiment	**Value (cm^3)**	**Reduction (%)**	**Value (cm^3)**	**Reduction (%)**
Unprotected	3033.8		1400.4	
1-S	2089.0	31.1%	19.5	98.6%
2-S	1805.4	40.5%	44.9	96.8%
3-S	2283.8	24.7%	42.6	97.0%
4-S	829.2	72.7%	19.9	98.6%
1-M	1542.2	49.2%	29.3	97.9%
4-M	938.0	69.1%	403.4	71.2%
1-L	996.1	67.2%	996.1	28.9%
4-L	1524.0	49.8%	865.2	38.2%
1-XL	1095.3	63.9%	1095.3	21.8%

Table 6. Percentage reduction of each test

The previous table presents the reduction percentage of the volumes of each test. It should be noted that the total reduction of the scour volume is less meaningful than the reduction of the upstream scour volume because the reference value taken to calculate this percentage is the unprotected scour volume which is related to the area around the pier. Meanwhile, the volumes data of the total scour volume for tests 1-S,2-S,3-S,4-S, and 1-M are more related to the scour surface presented after the area where the net was placed. Nevertheless, the situation is different for the tests 1-L,1-XL, 4-M, and 4-L since these scour surfaces are developed in the area where the net was placed, so the reference unprotected value is a more significant value to measure the reduction percentage.

Likewise, the analysis for the reduction percentage for the upstream scour volume is more consistent as they conserve the same reference value to measure the reduction. However, the upstream scour volume for test 1-S,2-S,3-S,4-S, and 1-M registered very high reduction rates, which could be associated with the impermeable feature of the mesh size against sediments but additionally to the over constrain effect of the placement nails which is helping the net to behave with very high stiffness.

Figure 50. Photograph scour hole- unprotected test

Figure 51. Photograph scour hole - test 1-S

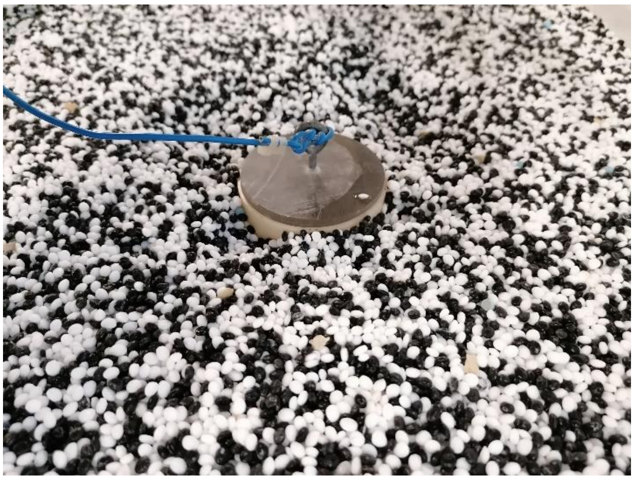


Figure 52. Photograph scour hole - test 1-M

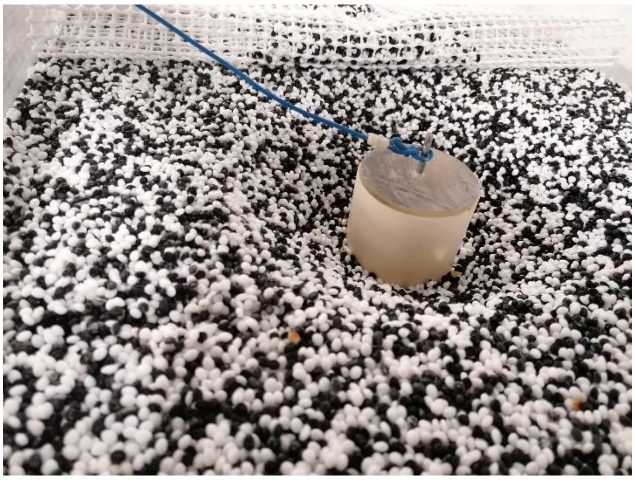


Figure 53. Photograph scour hole - test 4-M

Figure 54. Photograph scour hole - test 4-L

Figure 55. Photograph scour hole- test 1-XL

In the same way, the volume accumulated due to the scour process where the sediment was moved and collected until it reached a higher level than the initial bed was registered and resumed in the following graph for the total area. In the case of tests 1-S, 2-S, 3-S, 4-S, and 1-M, it was reported a small accumulated volume compared to the volume of tests 1-L, 1-XL, 4-M, and 4-L, all due to the different mesh sizes. In the case of the mesh size L and XL, the feature of a net permeable to the sediment allows a bit more free movement of these, increasing the likelihood of accumulation of sediments in the bed. Moreover, within the results of the mesh size S, the arrangement of protected area 1 influenced a higher sediment accumulation compared to the others.

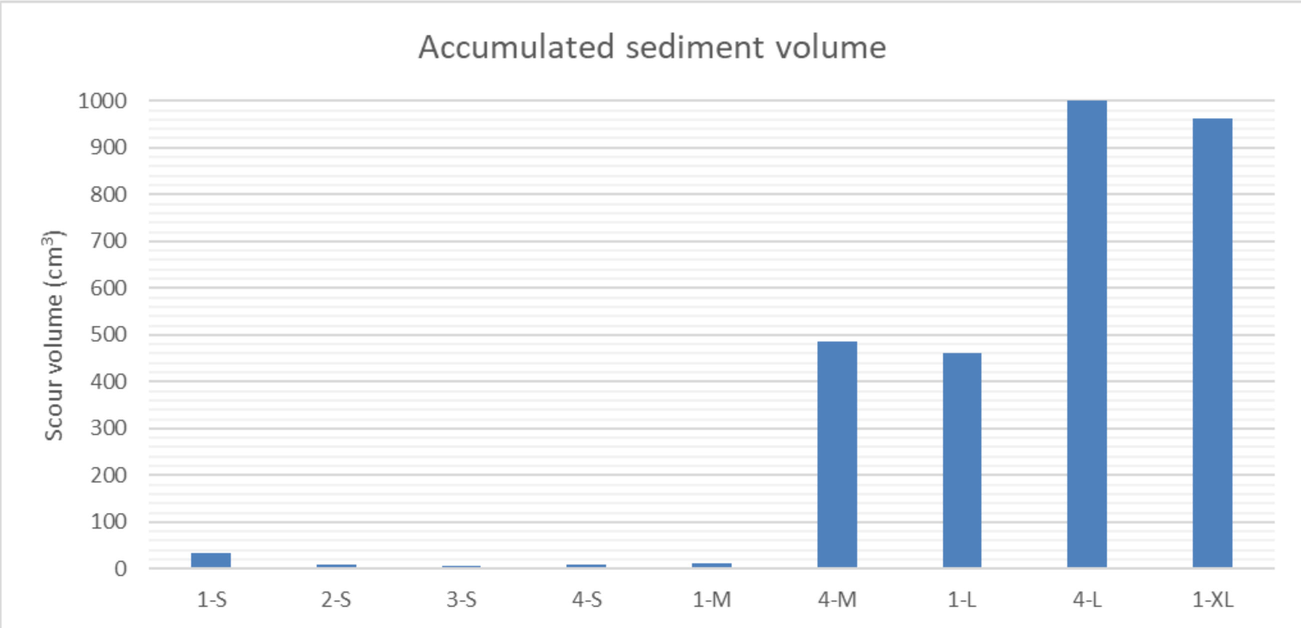


Figure 56. Accumulated sediment volume

To assess the behavior of the nets in time and have notions of the level of the scour hole, some temporal measures were established. Unfortunately, the survey process with the point gauge is a time-consuming method, thus, the temporal measures were only at 2 hours, 4 hours, and 6 hours. Furthermore, the temporal measurements were not the same for all the size mesh. For example, in the case of mesh size as S or M, the aperture of the mesh does not allow to take measures in the area protected by the net, hence, the temporal measurements were done to the scour surface that appears after the net area ends. On the other hand, mesh sizes like L and XL allow to take temporal measures in the area protected by the net, but due to the time consumed by the survey and the difficulty to measure with the water flowing, the temporal measures for this mesh size were only for the upstream part of the pier. This can be seen in the following graphs.

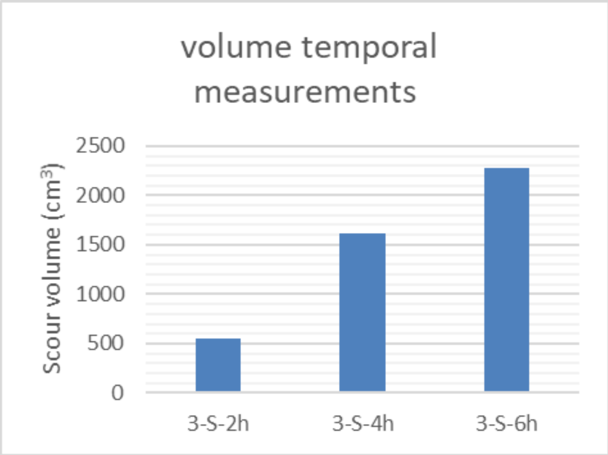


Figure 57. Volume temporal measurements test 3-S

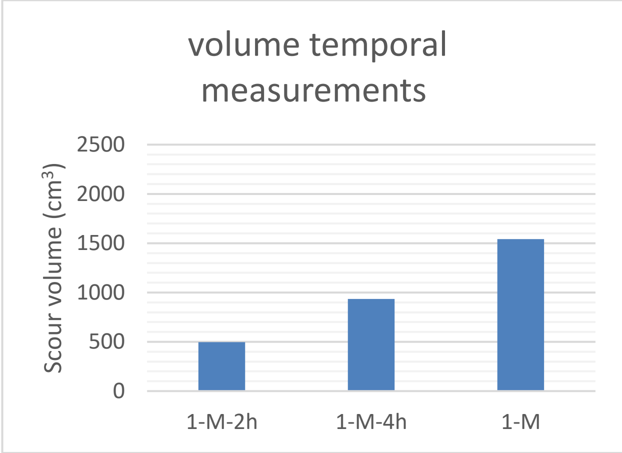


Figure 58. Volume temporal measurements test 1-M

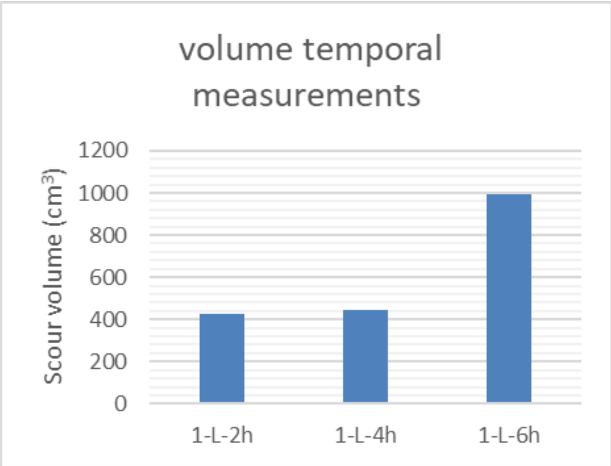


Figure 59. Volume temporal measurements test 1-L

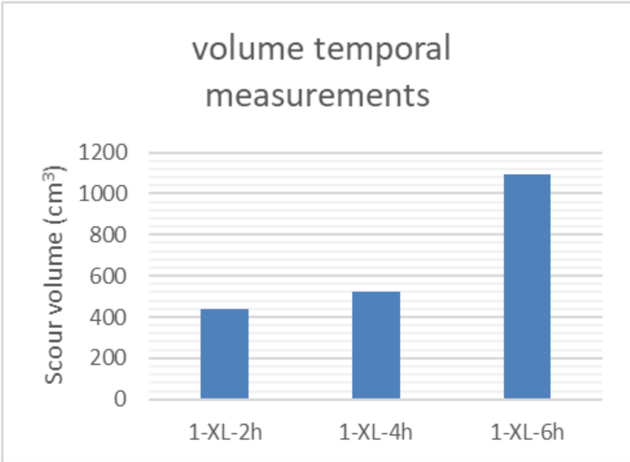


Figure 60. Volume temporal measurements test 1-XL

Measured volumes register expected trends from mesh sizes S and M, which report an increased volume rate but require more time to find the equilibrium and reach an asymptotic value. On the other hand, the mesh sizes L and XL have reported the highest change between 4 and 6 hours. The reason for this behavior is given that in the experimental facilities there is a limit for the gauge to reach zones close to the pier while the water is flowing, thus, the temporal measures upstream the pier did not include a portion that represents a difference of volume between this range of time, although not all of it is related to this problem, part of it is tied to the scour process.

The second analysis to assess the performance of the nets was developed using the scour depth during each test compared to the unprotected test. Figure 61 shows the results. Firstly, not in all tests, it was possible to measure the scour depth due to the mesh size, thus, mesh sizes L and XL have more temporal points, not only at the end of the experiment like the other tests. This scour depth was measured in the upstream face of the pier where it supposed to be present the higher scour depths.

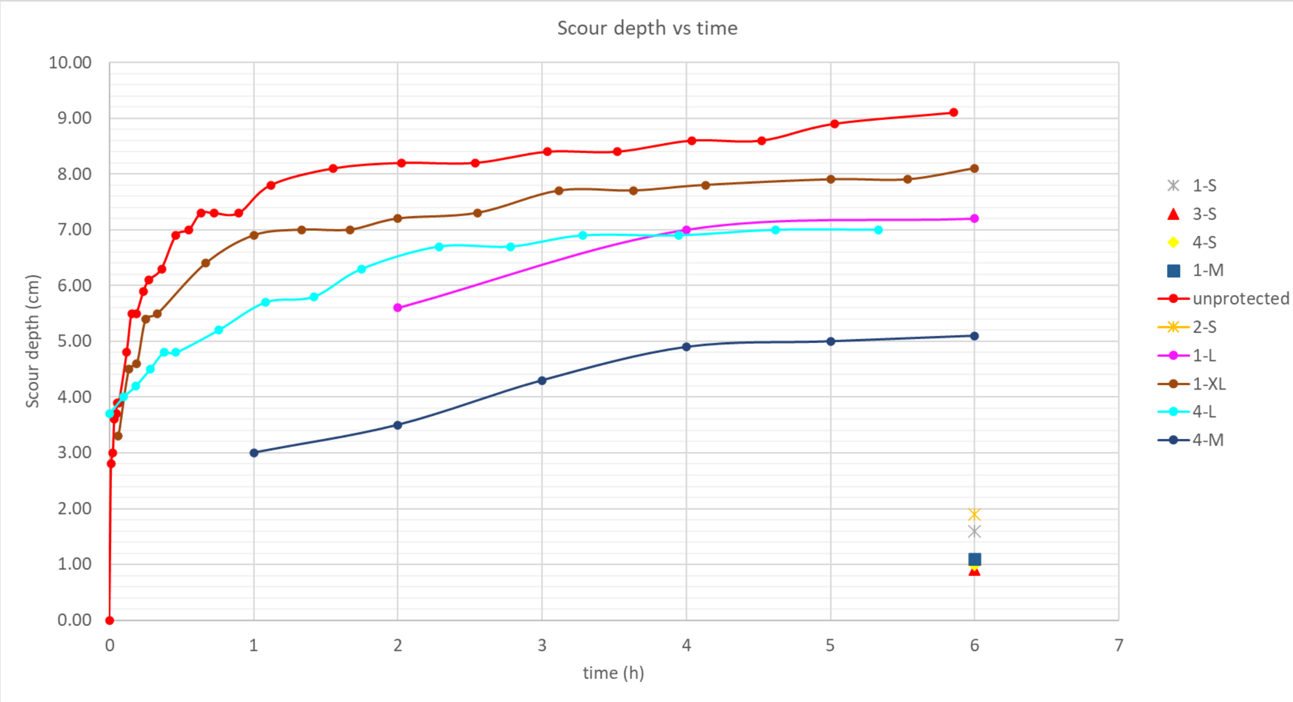


Figure 61. Scour depth vs time (all tests)

Nevertheless, the trends presented by the test that have temporal scour depths are consistent with the fact that increasing the mesh size will expose more the bed under the net and lead to a higher scour depth. In the case of tests 1-S, 2-S, 3-S, 4-S, and 1-M, even though it was not possible to take temporal measures, by observation of the experiment it was possible to determine that scour depth values were low. They were achieved over the first hours and then presented little variations until the final value, as in the expected clear-water scour process. Moreover, most of the eroded material in these tests goes out through the space between the end of the net and the pier zone, as highlighted in red the figure 62.

Additionally, in terms of results, the difference between test 1-S,2-S,3-S,4-S and 1-M is not highly significant and almost all of them reduce in the same magnitude the scour depth. Meanwhile, the tests 1-XL, 1-L, and 4-L follow the expected trend of the net with a permeable condition of the sediment. Nevertheless, a special condition was observed between net 4-L and 1-L, the effect of the configuration of area 4 make the test 4-L arrive 1 hour early to the scour depth of 5.7 cm than the test 1-L, but at the end, both experiments end with the same final scour depth. Moreover, test 4-M behaves differently compared to the expected from test 1-M, creating a representative decrease in the scour depth but not as good as with test 1-M. However, it is important to remind that the test 4-M creates less total scour volume than 1-M.

Figure 62. Photograph weak area between pier and net

The volume calculations for the data analysis were carried out through digital surfaces built with the surveyed sections and created in the software CIVIL 3D after the end of the experiments. The following figures resume the final surfaces for each test done in the digital model. These show better the shift in the scour surface after the area protected by the net. For instance, this shift in the scour surface occurs when the pier is lifted and the vortex appears and start at first to move the sediments in the zone upstream of the pier, but due to the presence of the net the sediments cannot move freely, and the scour process changes compared to the standard.

In the following figures, the brown surface represents the initial bed, the yellow one represents the scour surface, and the white net represents the location of the net in the experiment. Hence the yellow zones over the brown ones represent the accumulation of sediments. Also, the flow direction is indicated by the blue arrow.

UNPROTECTED TEST

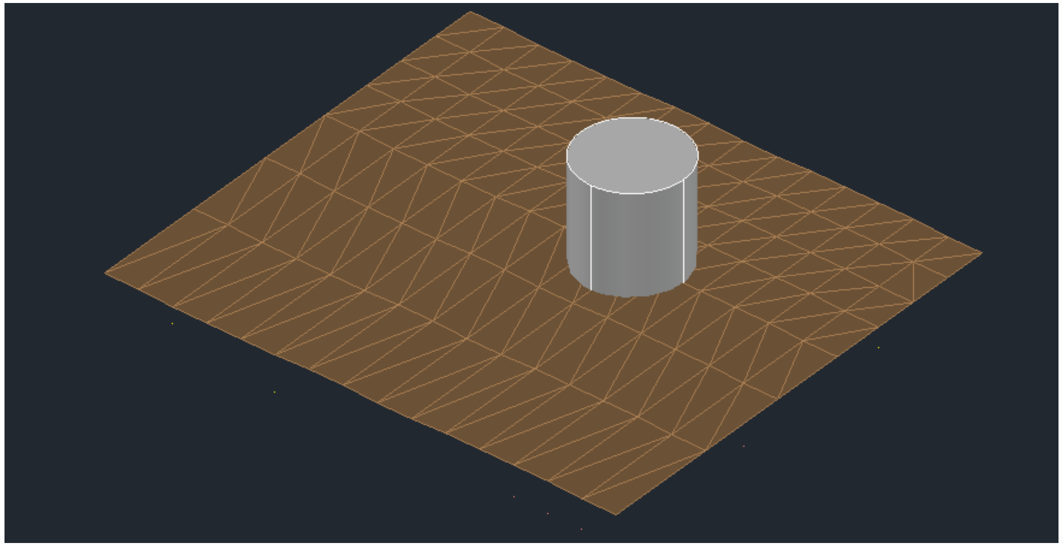


Figure 63. Digital bed surface unprotected test

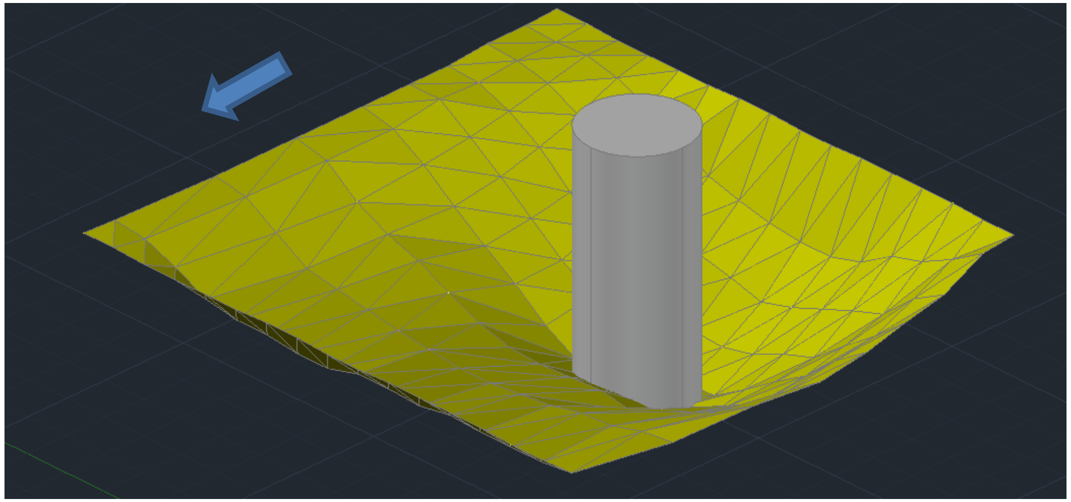


Figure 64. Digital scour surface unprotected test

TEST 1-S

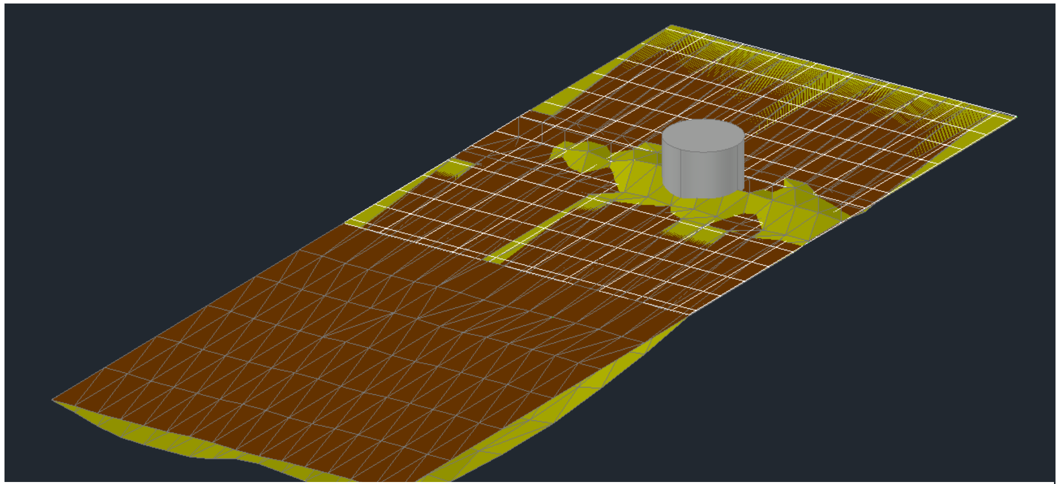


Figure 65. Digital bed surface test 1-S

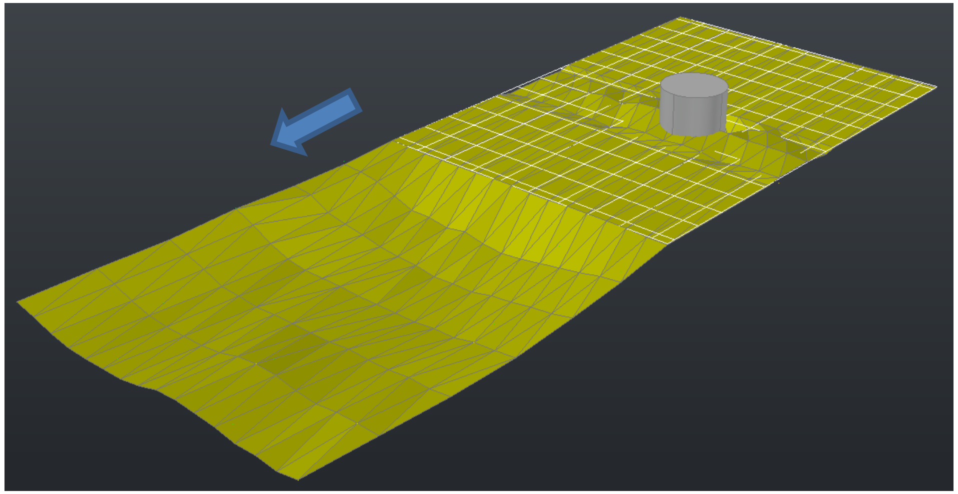


Figure 66. Digital scour surface test 1-S

Figure 67. Photograph scour surface close the Pier test 1-S

Figure 68. Photograph bed surface after protected area test 1-S

TEST 2-S

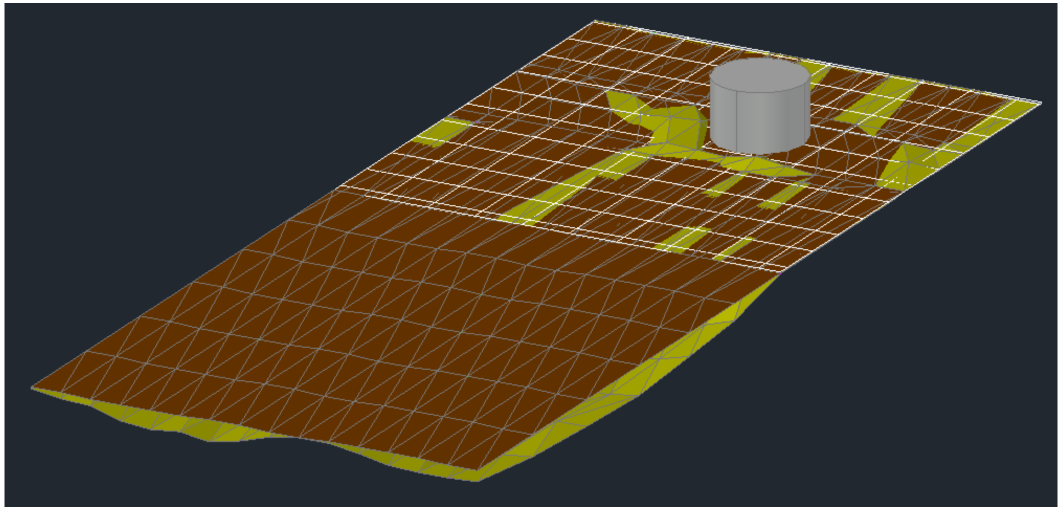


Figure 69. Digital bed surface test 2-S

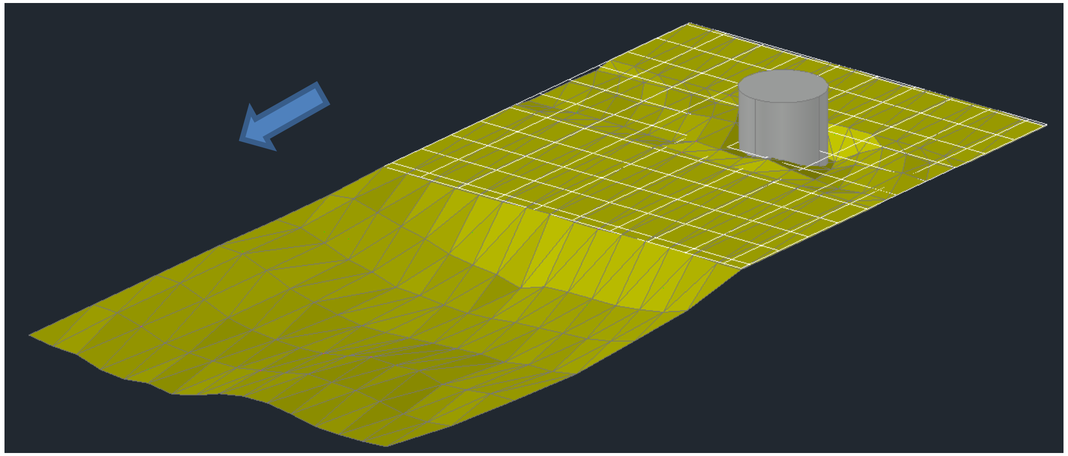


Figure 70. Digital scour surface test 2-S

Figure 71. Photograph scour surface close the Pier test 2-S

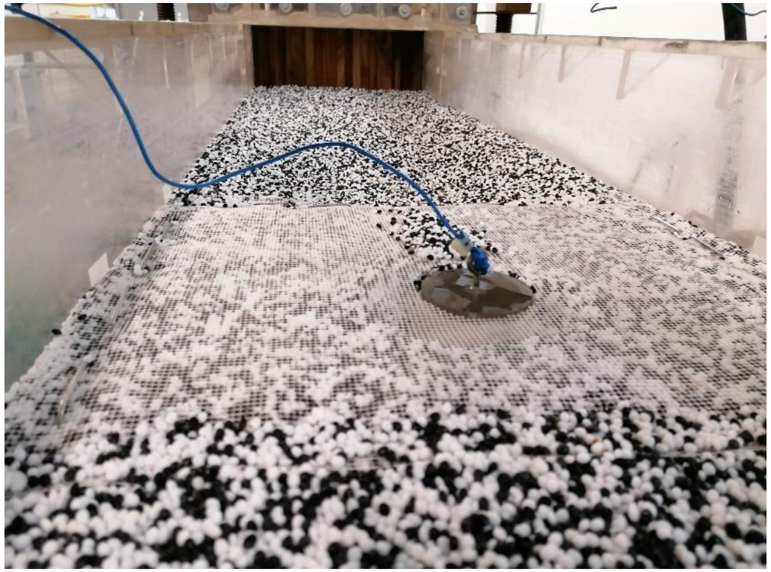


Figure 72. Photograph bed surface after protected area test 2-S

TEST 3-S

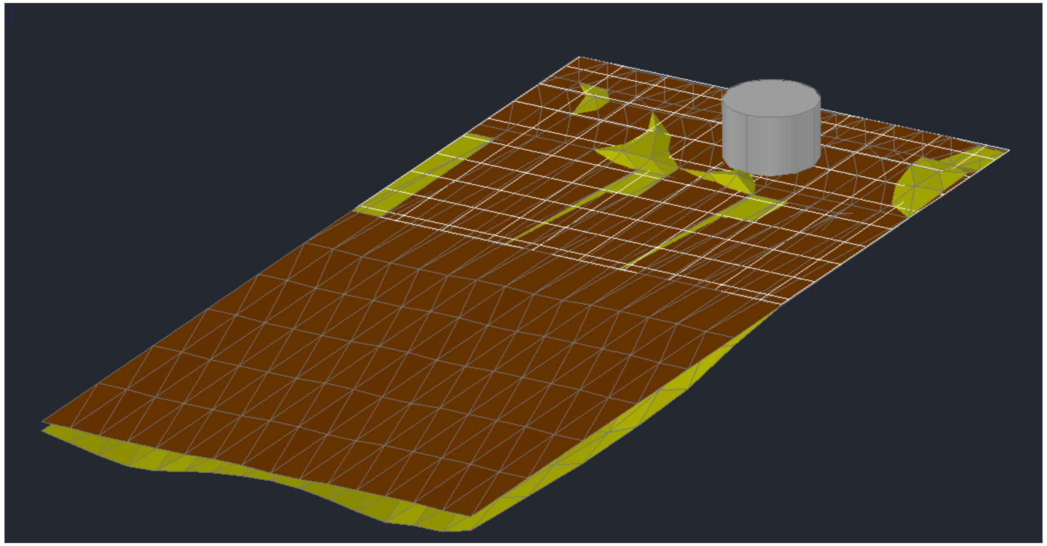


Figure 73. Digital bed surface test 3-S

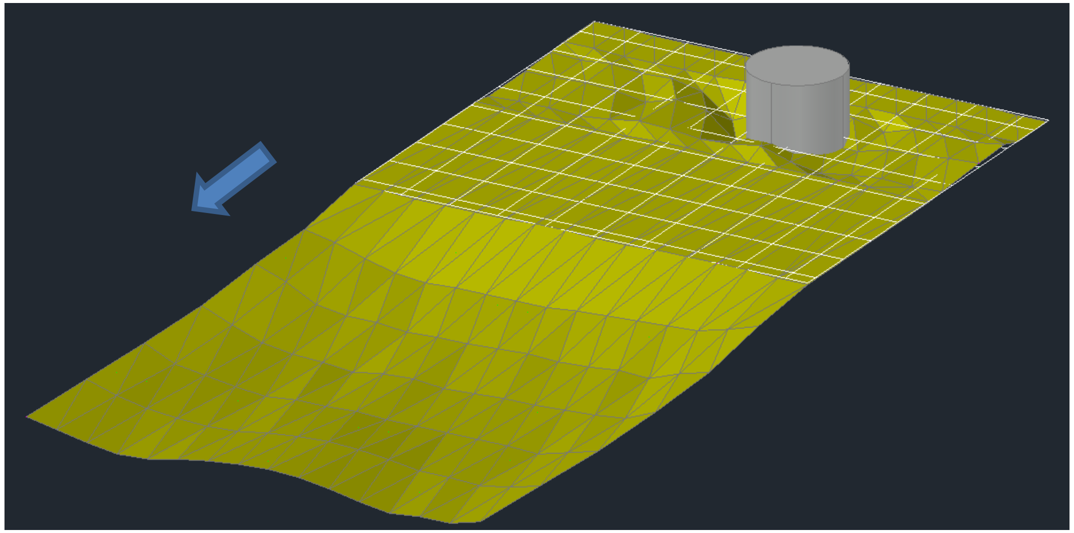


Figure 74. Digital scour surface test 3-S

Figure 75. Photograph scour surface close the Pier test 3-S

Figure 76. Photograph bed surface after protected area test 3-S

TEST 4-S

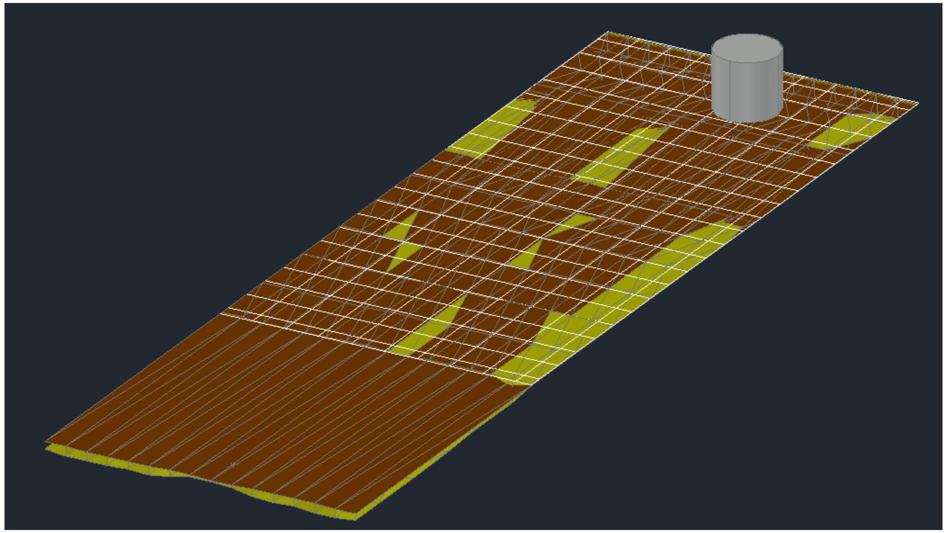


Figure 77. Digital bed surface test 4-S

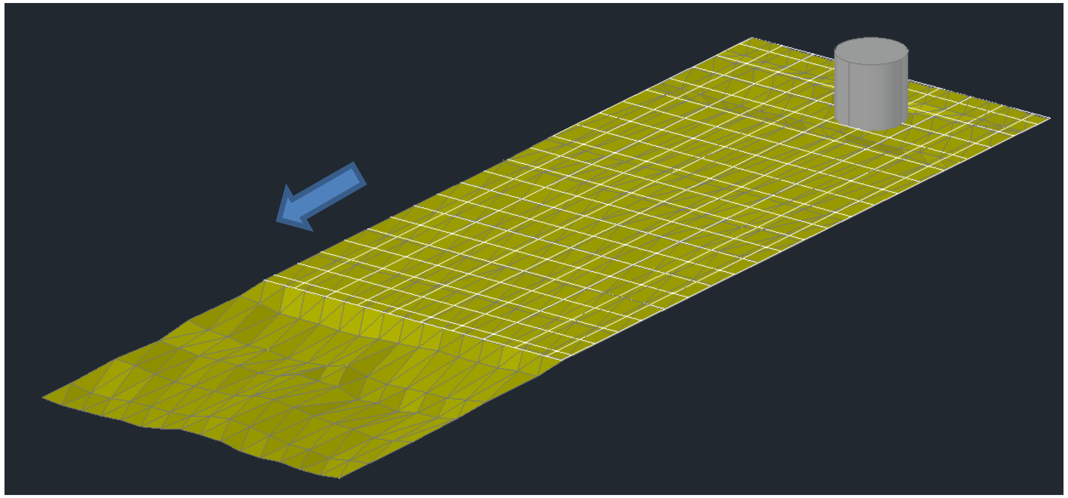


Figure 78. Digital scour surface test 4-S


Figure 79. Photograph scour surface close the Pier test 4-S


Figure 80. Photograph bed surface after protected area test 4-S

TEST 1-M

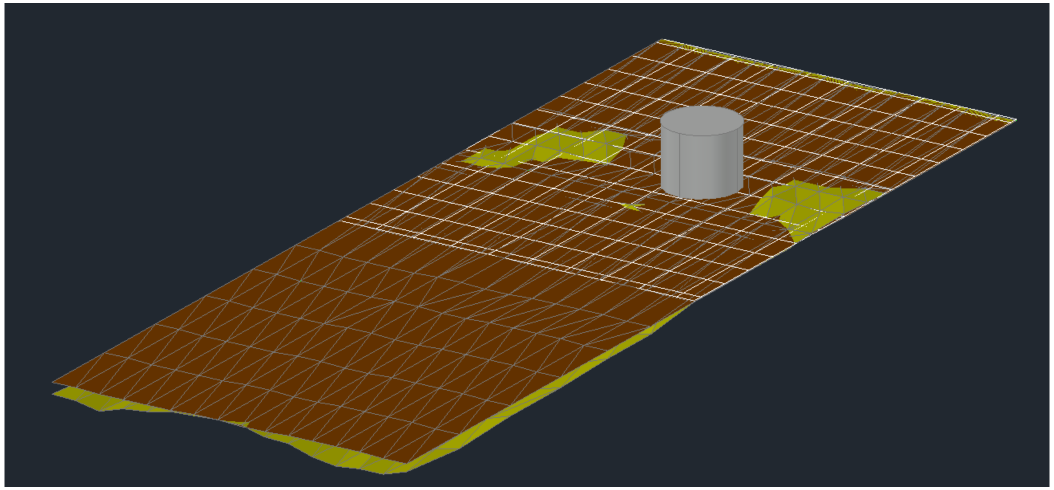


Figure 81. Digital bed surface test 1-M

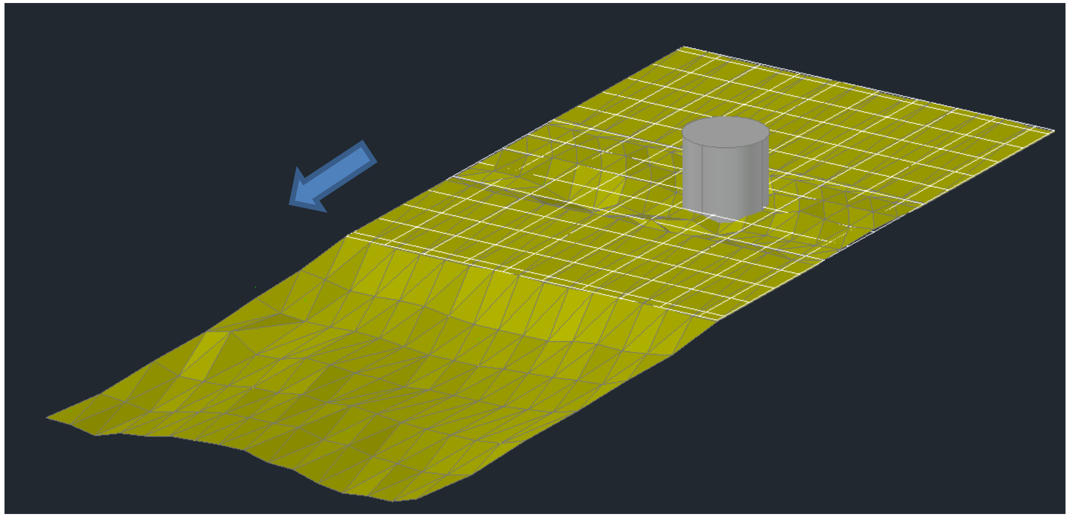


Figure 82. Digital scour surface test 1-M

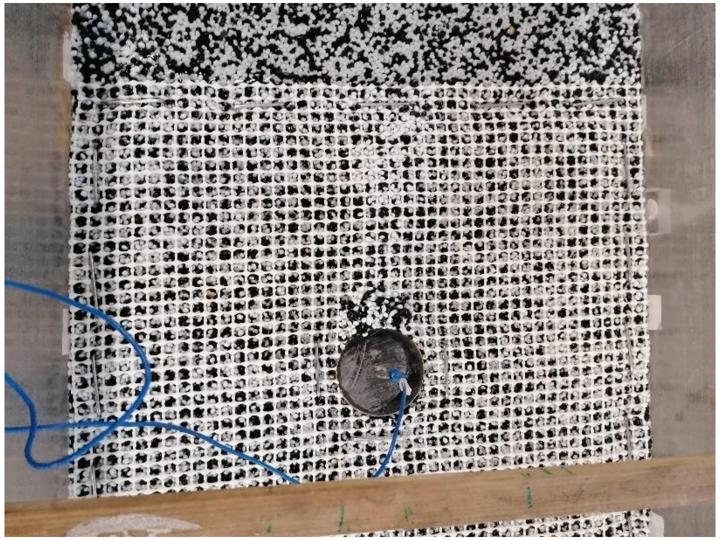


Figure 83. Photograph scour surface close the Pier test 1-M

Figure 84. Photograph bed surface after protected area test 1-M

TEST 4-M

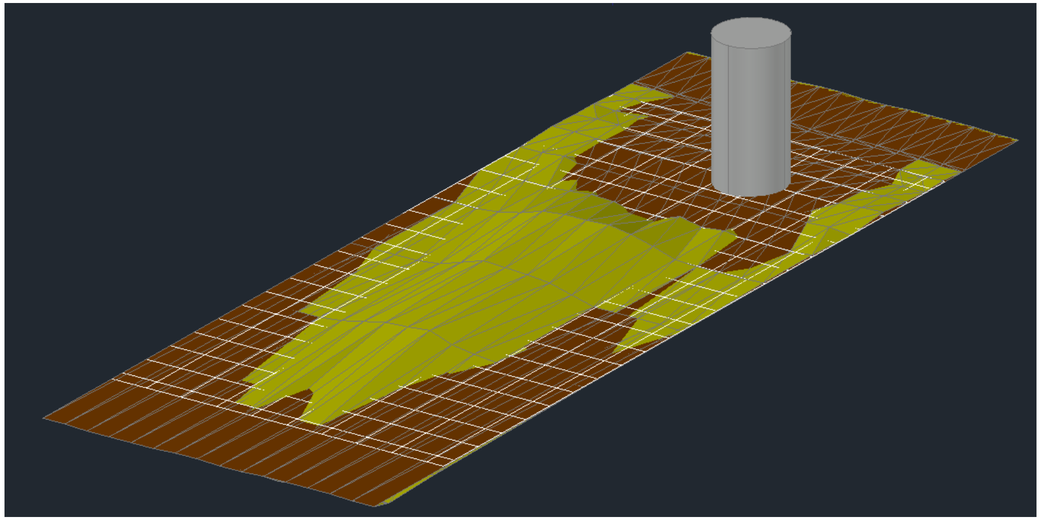


Figure 85. Digital bed surface test 4-M

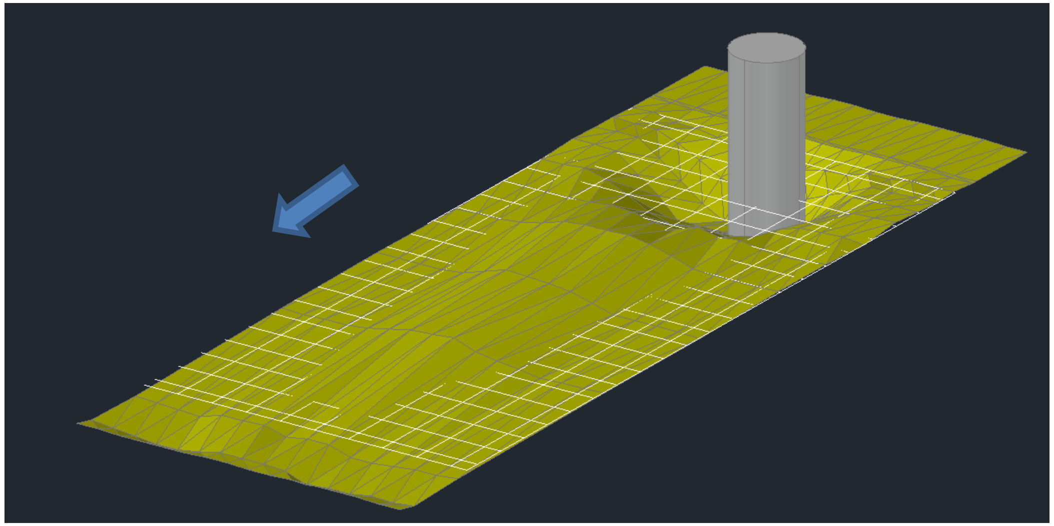


Figure 86. Digital scour surface test 4-M

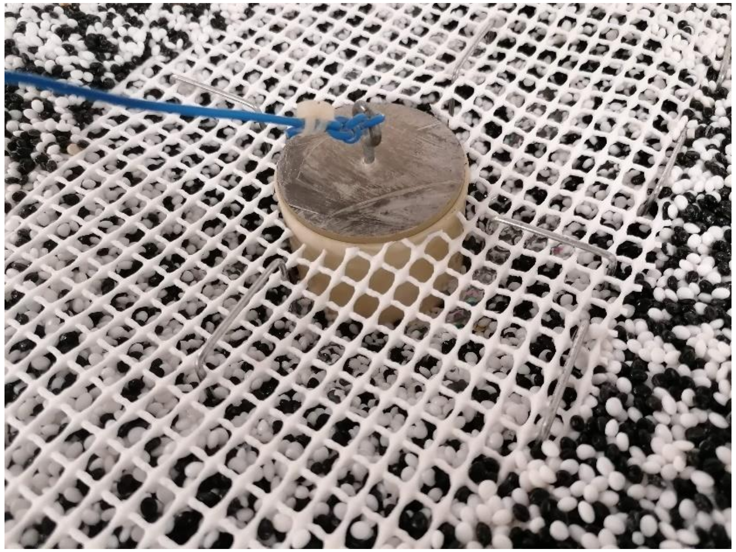
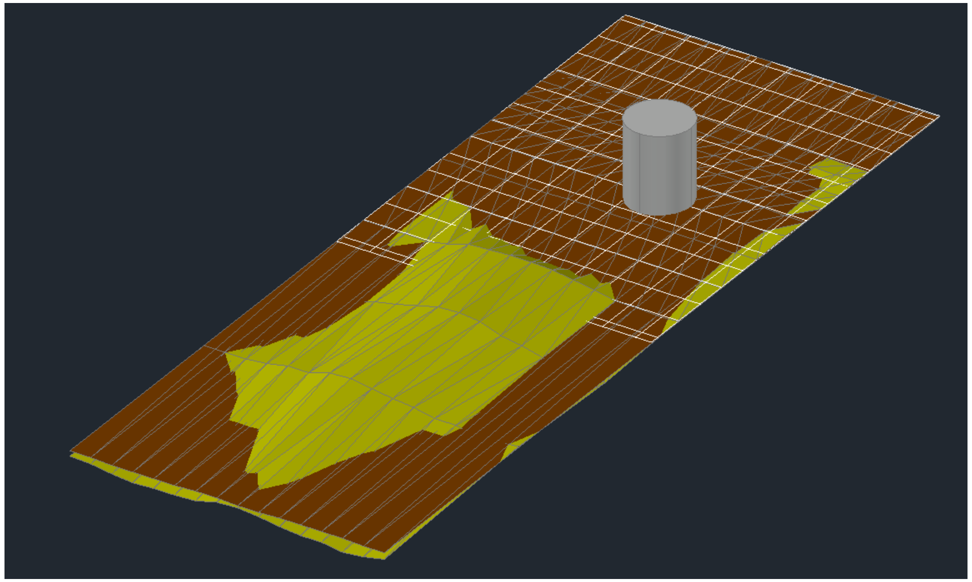
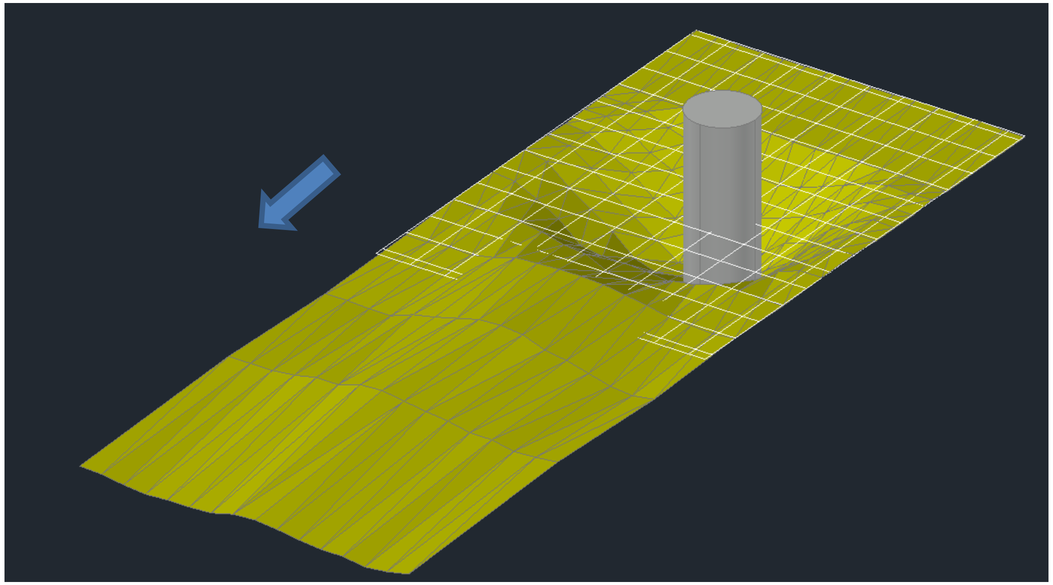
 *Figure 87. Photograph scour surface close the Pier test 4-M*	 *Figure 88. Photograph bed surface after protected area test 4-M*
TEST 1-L	
 *Figure 89. Digital bed surface test 1-L*	 *Figure 90. Digital scour surface test 1-L*

Figure 91. Photograph scour surface close the Pier test 1-L

Figure 92. Photograph bed surface after protected area test 1-L

TEST 4-L

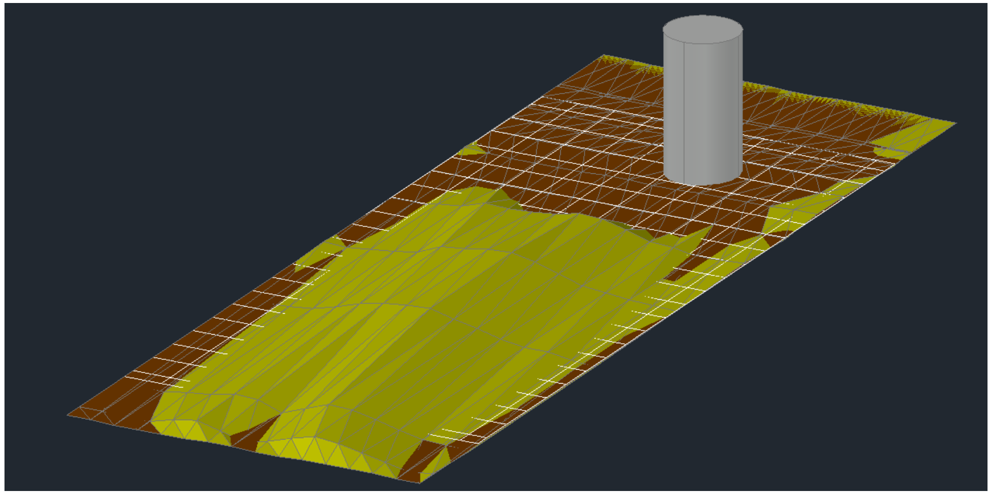


Figure 93. Digital bed surface test 4-L

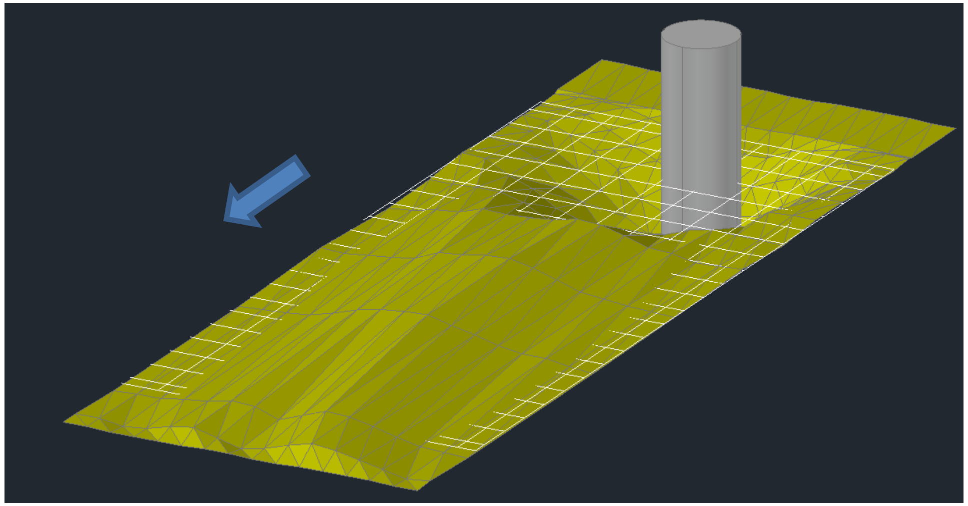


Figure 94. Figure 96. Digital scour surface test 4-L

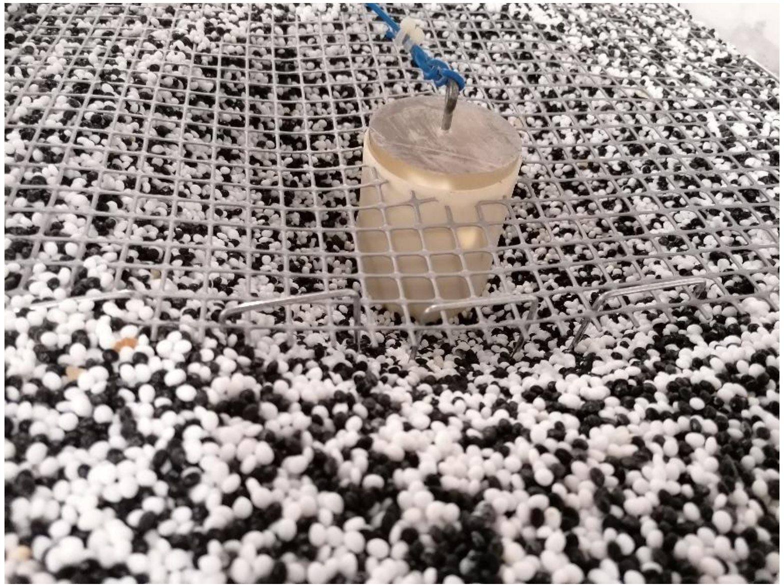


Figure 95. Photograph scour surface close the Pier test 4-L

Figure 96. Photograph bed surface after protected area test 4-L

TEST 1-XL

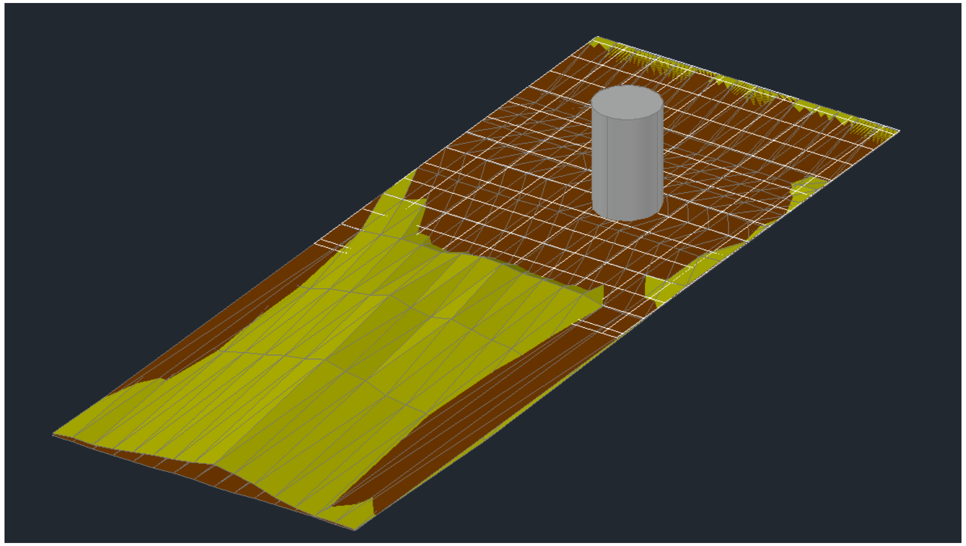


Figure 97. Digital bed surface test 1-XL

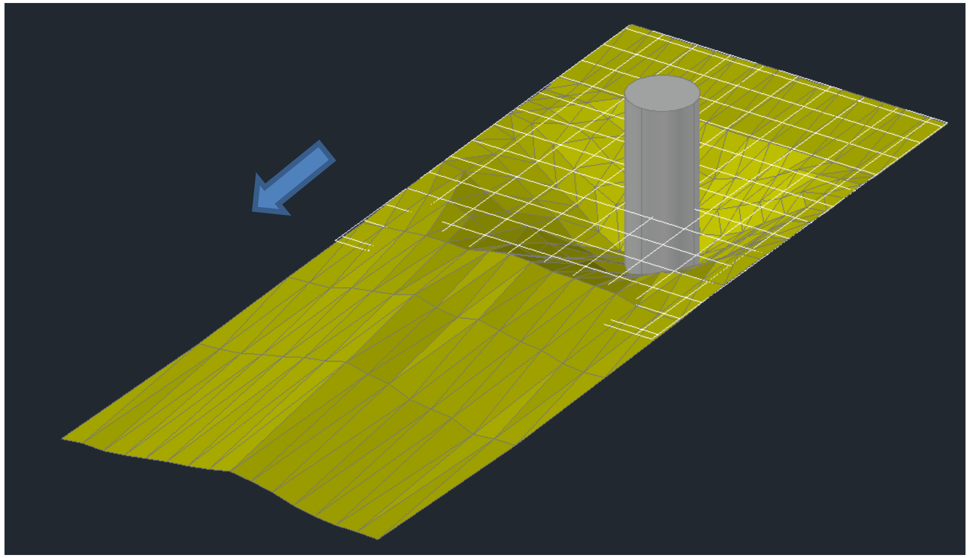


Figure 98. Digital scour surface test 1-XL

Figure 99. Photograph scour surface close the Pier test 1-XL

Figure 100. Photograph bed surface after protected area test 1-XL

Truly, the geo-carpet system is aimed to protect the pier from scour process but at the same time try to do not perturbate significantly the bed and keep the conditions as stable as possible. As can be seen in the digital surfaces and the table of reductions. The net not only can be assessed as the reduce in the scour volumes and depths, but also in the capacity to keep the bed sediments without significant changes. The following graph resume the scour volume upstream the pier and the scour volume only in the zone after the net area ends. These volumes are presented in a comparative way to choose the most meaningful experiments as the ones with the best general performance.

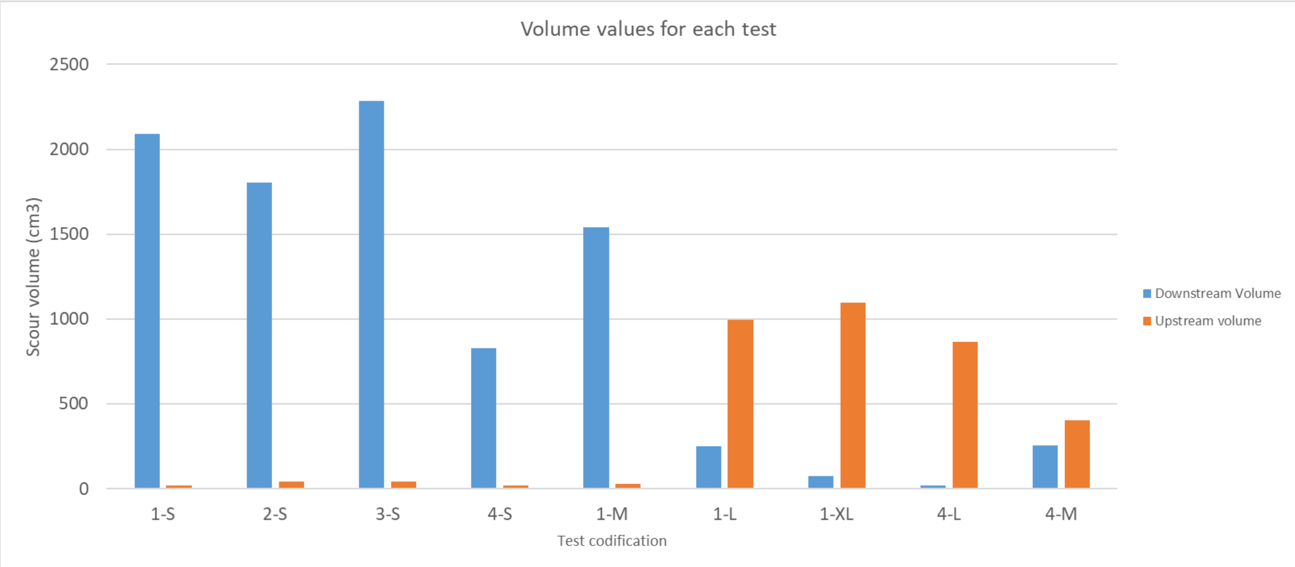


Figure 101. Volumes values-(upstream the pier and after the net area ends)

Based on the previous results, tests 4-S, 4-M, and 1-M are the ones with the best general achievements. The best test was 4-S which was able to reduce by 98.6% the scour volume in the area upstream of the pier and at the same time keep the bed sediment with low alterations. However, it is a configuration that requires more material and nails to achieve these goals. The second-best performance was the test 1-M which reduces the scour volume upstream the pier by 97.9% keeping the fifth less perturbed bed sediment. It achieved good results with fewer materials which gave it the benefit over the other arrangements. Finally, test 4-M is the third-best test with a good balance between total scour volume and upstream scour volume. This net achieved a reduction of 71.2% in comparison to the unprotected configuration, keeping the bed without alteration in terms of scour zones but presenting a zone with high sediment accumulation.

In addition, these volumes show the relationship between size mesh and scour volume in the zone after the net is placed. It shows that mesh size increases the amount of scouring after the net zone decrease. The same happens with the accumulation of sediments, if the mesh size increases, the cumulative sediment volume increase.

Using the previous analysis of the named parameters to assess the performance of the net system to decrease the pier scour one last relationship was determined to find an outcome that helps us to size possible influences of this system in other bed sediments. This outcome is the graph in figure 102, “effectiveness curve”. It allows checking the effectiveness of scour volume reduction upstream of the pier in terms of the configuration of the area (1,2,3,4) and the ratio between the mesh size of the geo-carpet and the mean sediment size.

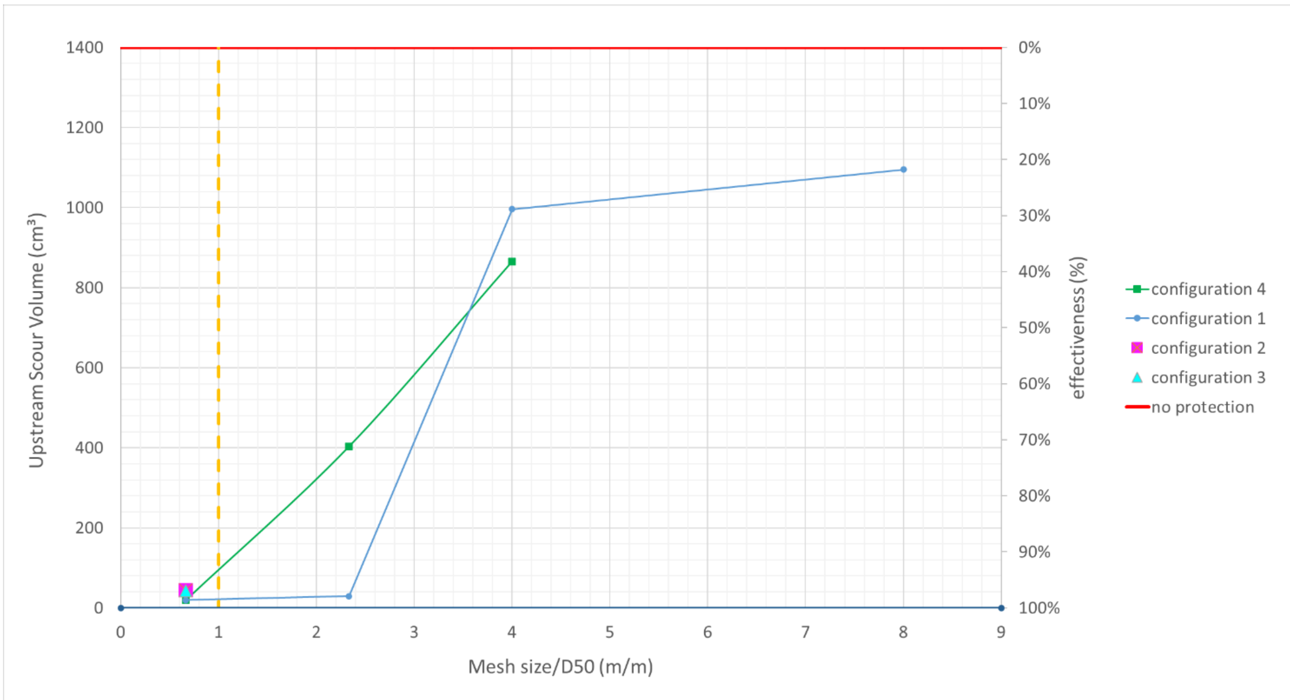


Figure 102. Effectiveness curve

The previous graph shows the interaction between different area configurations and the ratio between the mesh size of the geo-carpet and the mean sediment size, compared to an asymptotic value representing a non-protected state. This value was chosen because if the ratio increases mean that the size mesh increases to infinity, thus, it is representing a non-protected state. On the other hand, it represents the level of protection upstream the pier that the geo-carpet can provide, even when the mesh size is higher than the mean sediment size, this threshold is marked by the orange line for values greater than 1.

The effectiveness curve has limitations in the configurations due to the lack of time to develop all the points of each configuration. However, these represent the expected level of the scour volume for basic values of configurations 2 and 3, but in the case of configurations 1 and 4 which were the most effective in terms of results from the experimental campaign, it includes more points. Configuration 4 had a strong influence on the experiment with size mesh M, changing the shape of the graph but converging close to configuration 1 when the mesh size is 4 times bigger than the mean sediment size. Likewise, in configuration 1, after this limit, the increase rate of the scour volume decreases and starts to approximate more slowly to the unprotected value.

4.3. Comparison with other methods

the previous results of the net system as countermeasure for pier scour can be compared against other methods as collars and geocontainers. This study can compare the results, but just in terms of the studied variables as in the case of the scour depth. The results of the experimental campaign will be compared with the effectivity of the experiments done in the reference [20] where a similar system is used but instead of the net is used a geotextile layer as a membrane over the sediment.

Comparison between different experimental campaigns is not possible in all the cases, for instance, in the research of the geotextile layer, the time of each test was 54 hours while the present study was only 6 hours, but still, the comparison can be done until the time reached. Another inconvenience to compare these studies is that in the reference [20] only 2 tests can be assessed with the present result because the other experiments in this research present delays of more than 6 hours in the appearance of the scour thanks to the geotextile layer.

Both experimental campaigns have a difference between them as velocities, sediment size, and pier dimensions. This difference in the parameters makes it difficult for the task to compare results, but to approach the process in a simple way, first, we use the general unprotected curve since the data to compare in the experiments are the scour depths, which base on the unprotected curve to evaluate their effectiveness. As can be seen in the following figure 103 both unprotected curves are similar until 1 hour, then the curve related to the geotextile layer research tends to a higher scour value but not significantly different. Therefore, the quantities related to scour depth can be compared between them to have a notion of the behavior of the net system against the geotextile layer.

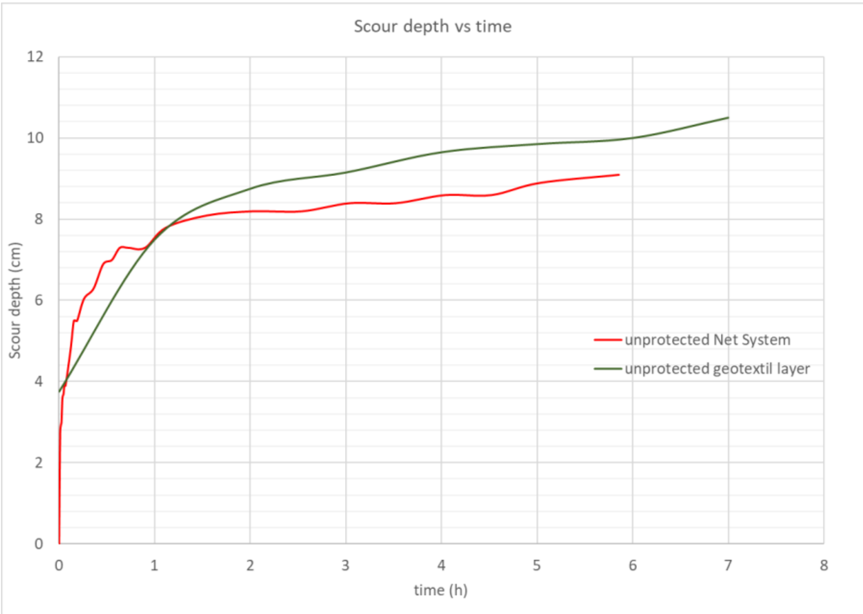


Figure 103. comparison unprotected curves of scour depths

As a result, the experiments were contrasted between them based on the scour depth of each one. The scour depths of the geotextile layer research were taken as a dimensionless value of scour depth divided by the pier diameter. The following graph compares them as a net scour depth and non as a normalized value in terms of depth. Tests 5 and 3 with the Neil and Bonasoundas pattern, were compared with the present study.

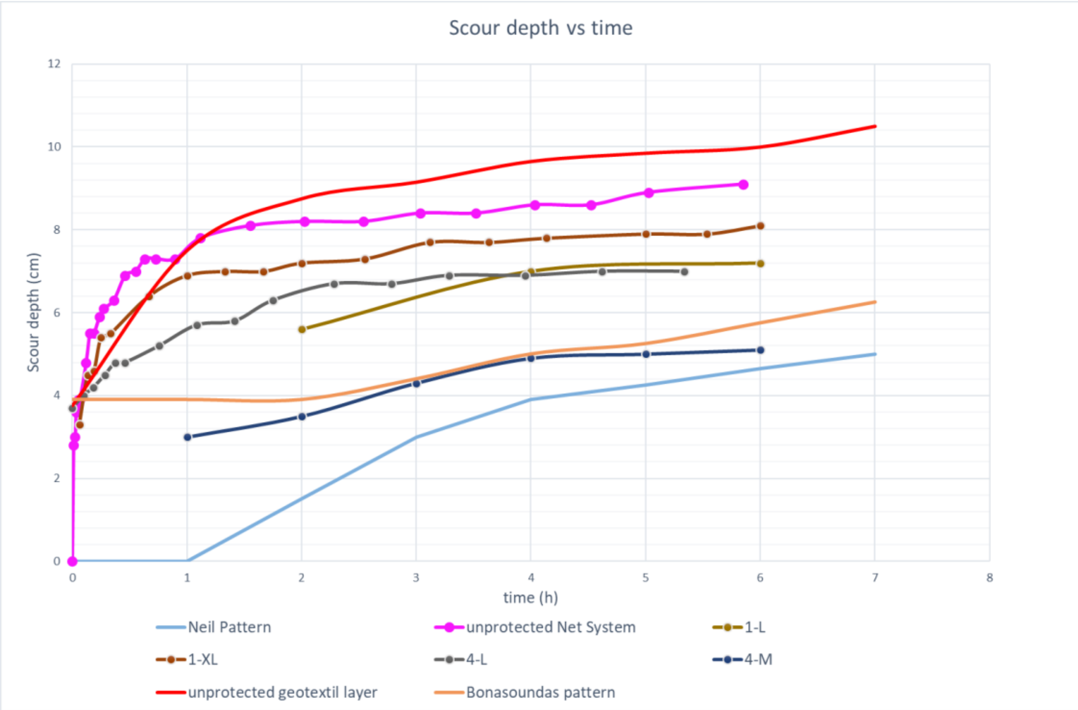


Figure 104. scour depths comparison between different systems

The previous graph assesses the performance of each system in terms of the scour depth achieved in each test. This graph only includes tests 1-XL, 1-L, 4-L, and 4-M as these are the experiments where the scour depth was measured upstream of the pier. However, in the geotextile layer research, only the Bonasoundas pattern present scour in the zone around the pier and can be more meaningful to compare than the Neil Pattern which did not present any scour around the pier. For instance, the result shows that the geo-carpet system of test 4-M could represent a slightly higher protection than the geotextile layer with the Bonasoundas pattern.

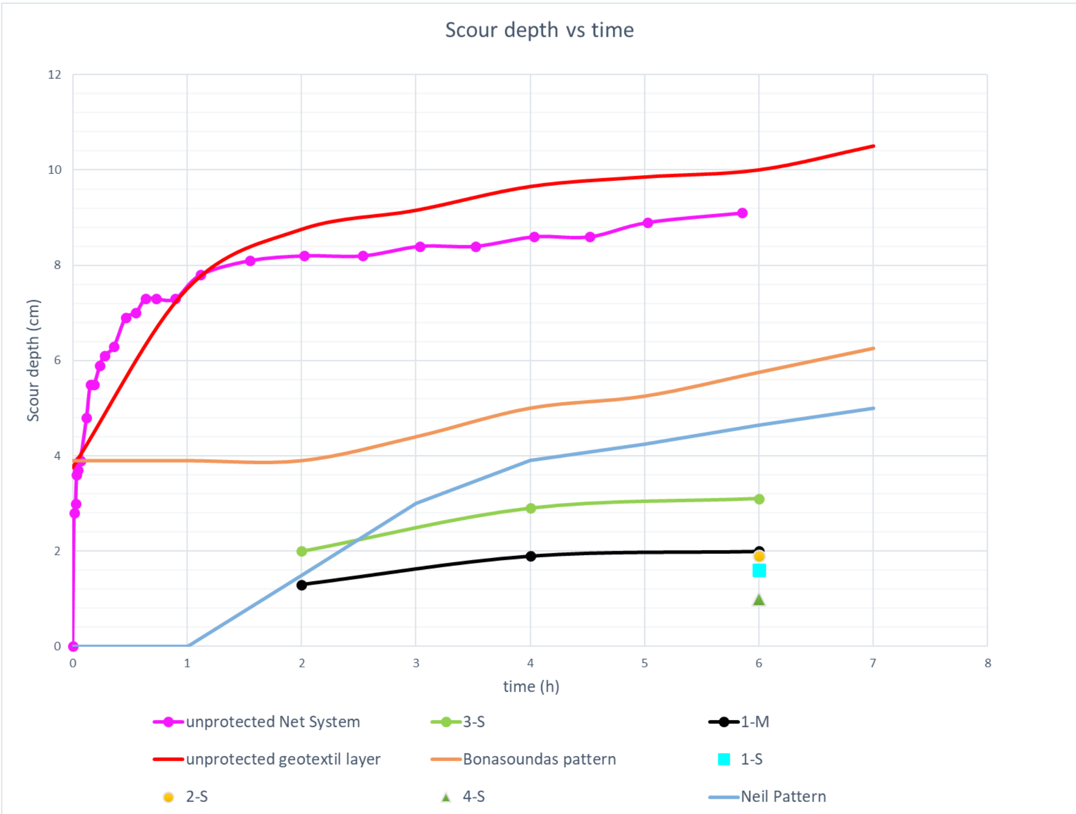


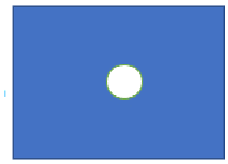
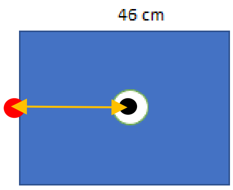
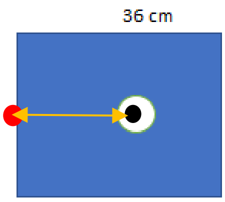
Figure 105. scour depths comparison between different systems

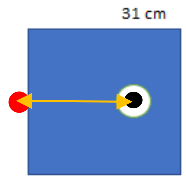
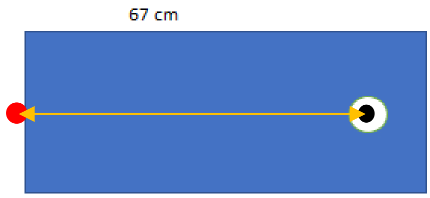
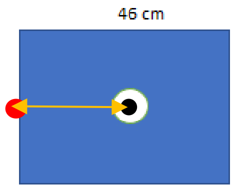
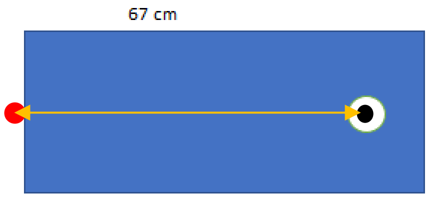
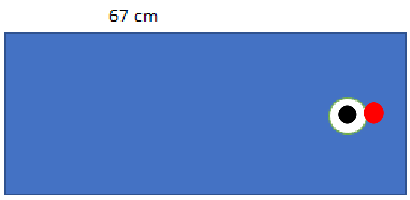
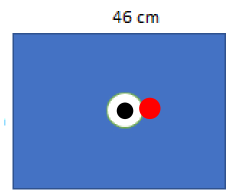
In the previous graph is presented the same experiments from the geotextile layer, but now they are comparing with the test 1-S,2-S,3-S,4-S, and 1-M. This test is compared apart from the others because the scour zone of this test is presented after the net area, hence the scour depths correspond to those scour zones. Consequently, assess these values with the Neil pattern is more meaningful because it presents the same behavior, and none scour zone occur around the pier and the scour depth were measured in the area after the net.

For instance, tests 1-M and 3-S report a better behavior than the Neil and Bonasoundas pattern and keep low values of scour depths. On the other hand, the performance of the test 1-M and 3-S before the two hours do not present a temporal measure to ensure that their behavior is better. From the observation of the tests in the experimental facilities, can be stated that the net system cannot delay the scour presence as the Neil pattern does for 1 hour. In addition, tests 1-S, 2-S, and 4-S do not present temporal measurements and are represented just as a measure of this arrangement against the values at 6 hours of the other methods. Moreover, the extension of the scour zone of the test 1-S, 2-S, 3-S, 4-S, and 1-M is bigger than the extension presented with the Neil pattern, but without further data is not possible to compare their volumes.

Is necessary to highlight that this analysis was done on a temporal scale of 6 hours, but the reference research of the geotextile layer was done for 54 hours presenting even higher scour depths. Thus, is important to do experiments with the net system with long durations to perform a more precise comparison between both countermeasure systems.

Another comparison can be done between these two studies for the case where the scour hole was shifted downstream due to the countermeasure. the following table resume the distance that was able to move downstream the location of the highest scour depth compared to the unprotected test. All the distance were measured from the center axis of the cylindrical pier drew as a black point in the figures and normalized in terms of D (pier diameter).

Test	Code	Location highest scour depth point	Location highest scour depth point (cm)	Location highest scour depth point/D (cm/cm)
1	UNPROTECTED		3	0.5
2	1-S		23	3.8
3	2-S		23	3.8

Test	Code	Location highest scour depth point	Location highest scour depth point (cm)	Location highest scour depth point/D (cm/cm)
4	3-S		23	3.8
5	4-S		59	9.8
6	1-M		23	3.8
7	4-M		59	9.8
8	1-L		3	0.5
9	4-L		3	0.5
10	1-XL		3	0.5

The previous results can be compared with the distance from test 5 from the reference [20] as in the case of the scour depths. In this case, the geo-carpet moved downstream the highest scour depth point 3.8 D for tests 1-S,2-S,3-S, and 1-M while for tests 4-S and 4-M it was moved 9.8D. these values are higher than test 5 from the reference [20] where the geotextile layer only could move the highest scour depth point by 2D. all the other tests did not change the position of the highest scour depth.

4.4. Factors to improve and future research

The geo-carpet system as a countermeasure for pier scours reports good advantages and benefits in the protection of piers. However, there are multiple factors to improve in this study to get a better knowledge of how the net system can be improved for any application in a real case and to know better the weaknesses of the system as well as failure modes.

For instance, multiple factors can affect the performance of the net like the protected area, mesh size, material, discharge value, scour condition, installation, and stiffness. In the case of the choice of the material, should be commented that this factor is key as it influences the stiffness and installation aspects. The materials used for this system are expected to behave with high stiffness in the axis in the direction of the flow in the channel but also have flexibility in the direction of the deformation of the bed. This property generates that all the protected areas keep high confinement and are connected as one to stand the force of the vortex around the pier. Moreover, the placement system used with the nails to locate the net in the bed augmented the consideration of the stiffness as the nails are representative large and constrain the net without affecting the flexibility in the bed sediments.

The assessment of all the tests possibilities among the different combinations of area configuration and mesh size is needed to give us a complete picture of which parameter could be more beneficial to protect the pier scour in terms of the proposed "effectiveness curve". Also, could lead to knowing which area configurations are not useful or which other areas or arrangements should be analyzed to improve the performance of the net system.

Secondly, further study around the size mesh M should be done to understand the strong change that generates the use of the configuration 4 in this mesh, giving a different behavior of the expected one compared to the case of the use of configuration 1 in this mesh, but with a good result. Moreover, new experiments of mesh size M should be fostered trying to avoid the problem with the floating effects of the material chosen for the mesh that was fixed with extra support made with nails.

Thirdly, complementary studies related to the variation in the nails placement system could help to understand better how big is its contribution to the stiffness of the net system and the reduction that can offer. Additionally, the nails placement system can be studied to optimize the number of nails required to keep the system functioning without over constrain the net and avoiding extra costs in materials.

it is widely recognized that most clear-water experiments can be tested for a long time until finding the equilibrium scour depth. Improving this parameter in the experimental campaign could give us a more global time scale to the clear-water scour phenomenon against another system to protect piers against scour.

Further development is needed to optimize the net system so it can bring multiple advantages in real-life cases. Particularly, more research can be done around topics like the area of protection, installation, material options, and durability. Firstly, exploring the variation of the protected area of the net could lead to optimizing the amount of material, especially in the horizontal direction of the channel. In the present study was analyzed only the variation of the area along the flow direction. The consequences of a lateral variation of the protected area are unknown but could be done with the work developed by Imamzadehei et al (2015) [20] as a starting point, having in mind its similarities to the result of this study in terms of the shifting of the scour zone.

The installation process requires further research to guarantee that the installation of the net system can be done in real-life cases to guarantee the confinement and stiffness needed to achieve good reductions rates in the scour depth to protect the pier. However, this installation counts with the disadvantage of the underwater placement of the net.

There are several materials available to manufacture the net, keeping in mind the new material technologies of the geosynthetics that currently include green proposals to impulse solutions that generate lesser environmental impacts and effects in the ecosystem. The same logic applies to selecting the materials or solutions available for the nails placement system of the net.

Finally, the durability of the net system is unknown as the experiments did not last long enough to detect any failure mode or if there is one. Thus, further studies are necessary to know the durability and maintenance required to keep the lifetime of the net.

5. Conclusions

This study attempts to introduce the implementation of a new countermeasure named "Geo-carpet," an approach to manage scour at piers as an alternative to the conventional methods. For this purpose, it was tested for scouring through laboratory experiments in clear water conditions at a cylindrical pier in free-surface flow. The development of this study focused on the introduction and exploration of the behavior of the proposed countermeasure and the discovery of possible ways to improve its performance.

Twelve tests were performed in clear water conditions with a flow discharge of 8.6 l/s during 6 hours for ten tests and 4 hours for the initial two. The shorter tests were useful to find technical problems in the implementation of the experiments. In contrast, the other ten tests were useful to analyze the factors that influence the system's effectiveness. However, there are multiple factors to focus on in detail, like the way to hold the geo-carpet to the sediment and the number of supports it needs to avoid an over-constrain situation. A deep understanding of these factors facilitates their control and enables them to recreate an environment more like the one that can be achieved in the implementation of real-life cases.

The number of tests developed in the experimental campaign was appropriate to perform an initial analysis on the influence of parameters like the protected area and the mesh size. The results report that the mesh size parameter is one of the most important variables that change the resulting scour surface and the expected scour depth. However, further research must follow up all the possible tests that include the variation of these parameters to complete an outlook of the behavior of the countermeasure. This can be seen in the suggested effectiveness curve, where there are configurations with no data for some cases due to the lack of tests to complete the graph.

Furthermore, the experimental campaign includes different configurations of protected areas around the pier, but only configuration 4 explores the variation of the protected area downstream of the pier. The results in the test of configuration 4 reflect a good performance in terms of reducing scour depth and the capacity to keep the bed sediment without big alterations after the pier area. Further research in the study of the influence of the geo-carpet's length should be fomented since the previous result highlights a pattern that could lead to creating a design parameter to guarantee a level of protection not only around the pier but also in the sediment bed downstream.

Contrary to the study in reference [20] that only considers the geometric change of the covered area, the present work included the variation of 2 parameters for the design of geo-carpets. These combinations of parameters between two direction protection areas and mesh size analysis could lead to an optimized geo-carpet prototype in terms of material and scour the surface. However, future tests using the optimized sizes from reference [20] would complement the results.

Current systems like geo-mattresses and geo-tubes have good properties against scour process and are avoided due to the installation difficulties that require these systems. Conversely, the geo-carpet has the advantage of being a net that could be more easily installed in the bed of rivers and does not need a filling process which could decrease the installation time. Nevertheless, this system should be first tested in real-scale cases to have better feedback. Moreover, the geo-carpet only was tested on the clear water scour condition. No further knowledge exists about the behavior in live-bed scour condition; hence, research in this direction should be fostered to have a wide point of view of the geo-carpet in any condition for future uses in real cases on rivers.

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