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Stability of blocks mats under flow conditions

TU Delft

Holcim

Stability of block mats under flow conditions

By

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Summary

In the last years the use and applications of block mattresses as protection systems has increased significantly. Despite the fact that the applications of block mats (either against flow or wave loads) are very commonly applied nowadays, there is not so much background regarding their stability. Consequently, the increase of knowledge on the stability of block mattresses is imperative. Main topic, therefore, of this Master Thesis project is the stability of block mats under flow conditions and the research will be done in co-operation with HOLCIM (the major supplier of placed block revetment systems and block mattresses).

Because of the fact that there is not so much background regarding the block mats, an extensive and good overview of literature (current background) is done in this Master Thesis. This literature study consists of several parts. First of all, there is a reference to the outfall structures that require bed protection. The basic characteristics of block mats, their production methods and their advantages are analysed next and the literature review ends with the analysis of the basic points of the existing stability formulas (especially Pilarczyk's empirical relation, which is mostly used) for the design of block mats under flow conditions.

Apart from the extensive literature review, which increases the knowledge on block mattresses, the background on the stability of these protection systems is enhanced by scale model tests (as a first approach in order to observe the trends and understand the paths that will be followed in the future researches). These scale model tests were selected to be done, since there was a lack of data (turbulence, velocity), with which a new stability parameter could be approached. Consequently, the scale model tests were the most appropriate of the available approaching methods in order to understand their behaviour, their stability under flow loads and take some measurements regarding the levels of turbulence and the velocity that may cause 'damage' to the block mattresses.

The tests were divided in three test series. The first test series refer to the behaviour of a block mat which is totally free to move and subjected to turbulent conditions. The second test series are about measurements of combinations of velocities and turbulence (in which the major importance of turbulence is proved and the trends for the stability are interpreted) that lead to failure and in the third test series the behaviour of a transition between two consecutive block mattresses is observed and examined.

Finally, the Master Thesis project ends with the interpretation of the results from the tests and the determination of the basic points for the follow-up program. In particular, the main recommendations for the follow-up program have to do with further lab experiments on the stability of block mattresses for the two main cases of failure ((1) flow overturning the upstream edge,(2) flow 'hitting' from above especially the downstream edge) that arose during this research.

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Symbol	*Definition*	*Unit*
α	slope angle	^{0}
b	exponent related to the interaction between waves and revetment type (roughness, porosity/permeability, etc.)	-
c_T	turbulence coefficient	-
C_T	blanket thickness coefficient	-
C_v	velocity distribution coefficient	-
C_{st}	stability coefficient	-
Δ	relative density	-
D	specific size or thickness of protection unit	m
D_p	effective diameter of the propeller	m
D_{n50}	median armourstone size	m
D_{50}	characteristic sieve size	m
f_g	gradation factor = D_{85}/D_{15}	-
ϕ	stability factor or function for incipient motion, defined at ξ_p=1	-
ϕ_{ar}	angle of repose	^{0}
ϕ_{sc}	stability correction factor	-
ξ_p	breaker parameter	-
g	acceleration of gravity	m/s^2
H_s	significant wave height	m
h	local water depth	m
k_{sl}	side slope factor	-
k_t	turbulence factor	-

k_h	velocity profile factor	-
k_s	roughness height	m
r	turbulence intensity	-
ρ	density	kg/m^3
S_f	safety factor	-
U	depth-averaged flow velocity	m/s
u_b	near-bed velocity	m/s
ψ_{cr}	critical mobility parameter of the protection element	-
ψ_u	system-determined (empirical) stability upgrading factor	-

1. Introduction

1.1 General introduction

Block mattresses or block mats are, nowadays, very commonly applied as protection in a large range of applications either against flow or wave loads. Specifically, this large range of applications contains offshore pipeline protection and stabilization, erosion and scour protection, protection of embankments and river banks (slope protection). The reason why block mattresses are increasingly used in many applications as protection system is due to the following advantages compared to discrete-unit armour systems such as quarry stone or individually-placed blocks which are the enhanced stability that block mats have because of the virtue of connection between adjacent blocks and their properties of being able to be laid quickly and efficiently even under water.

1.2 Problem definition (need for the project)

This project refers to the stability of block mats at the end of a weir, spillway, culvert or pipe. In this situation, there is a current problem and current load is induced by a discharge volume with high flow velocities. The most important aspects of this current problem are supposed to be the effects of large flow velocities and turbulence rates which will affect the required block thickness and the length of the bed protection.

Despite the fact that there are many applications in which block mats can be applied, there is not so much background regarding the stability of these protection systems. Moreover, during tests that have been done, where flow conditions were increased step by step a sudden failure was observed without any other early notice of damaging before. This phenomenon happened sometimes even earlier than it was expected from the stability empirical formulas that are used. In other cases, the required thickness of blocks that is calculated by the current stability relations appeared to be very conservative. All the above mentioned reasons make clear that there is need for optimization (better understanding) of the stability formulas and analysis of the design methods that are followed for the characteristics of the block mattresses (shape, weight, materials).

1.3 Objective

Formulated in one single sentence the MSc-graduate project can be defined as: 'Stability of block mats under flow conditions'. Therefore, the goal of this project has definitely to do with the recognition of the physical processes, which cause damage to the block mattresses, resulting in the increase of knowledge on stability of block mats. In addition, another objective of the project is to give guidelines regarding the use of block mats for different shapes and weights and under different types of flow. In order to achieve the goals of this project, an extensive and good overview of literature (current background) in combination with scale model tests (after analysing the possibilities for minimum scale effects) will be needed. The research will be done in co-operation with HOLCIM, which is a major supplier of placed block revetment systems and block mattresses.

2. Literature review

The chapter of literature review consists of several different parts. Firstly, a reference to the outfall structures that need bed protection is made, followed by the analysis of the characteristics and behaviour of block mats and geotextiles in this type of structures. The existing formulas for the stability of block mattresses under flow conditions will be analysed next and the chapter ends with a synopsis about the present knowledge which is the guide of this master thesis and the critical points that need to be determined in order to optimise the current stability formulas which is the main topic of this master thesis.

2.1 Outfall structures

The general scope of this thesis, as mentioned above, is to investigate the stability of block mattresses under flow conditions at the end of a weir, spillway, culvert or pipe. So, this part refers to the outfall structures and the corresponding characteristics that these structures have.

To start with, an outfall is the discharge point of a stream into a body of water, or alternatively it may be the outlet of a river, pipe or a sewer where it discharges into the sea or a lake. By the definition of the outfall it is understandable that outfalls are, also, locations where the stormwater exits a facility including pipes, culverts and other structures that transport stormwater. Characteristic examples of this type of structures are: gated or ungated weirs, spillways with stilling basins and culverts discharging to a stream or river.

First of all, a few things about spillways will be mentioned in order to understand how these structures work. Spillways consist of three parts:

- A sill at upstream end which controls discharge rate and accelerates the flow
- A steeply sloping chute where flow is maintained or increased
- A terminal structure where the flow returns to the river channel

A basic rule for designing spillways has to do with the fact that the chutes and the outlet tunnels must be straight because they are designed for supercritical free surface flow which is difficult to turn. The most important parameter according to this thesis is the protection of the last part of the structure where the flow returns to the river channel and the transition from supercritical to subcritical flow takes place leading to phenomena of increased turbulence and erosion (scour) downstream. Hence, a protected area should be downstream of the terminal structure in order to avoid scour which can dynamically endanger the stability of the whole structure if measures are not taken. A typical chute spillway is shown in Figure 2.1, where the three above mentioned parts of the inlet, slope and outlet are presented. Spillways are usually constructed in dams, which has as a consequence the flow velocities to be extremely high (>10 m/sec).

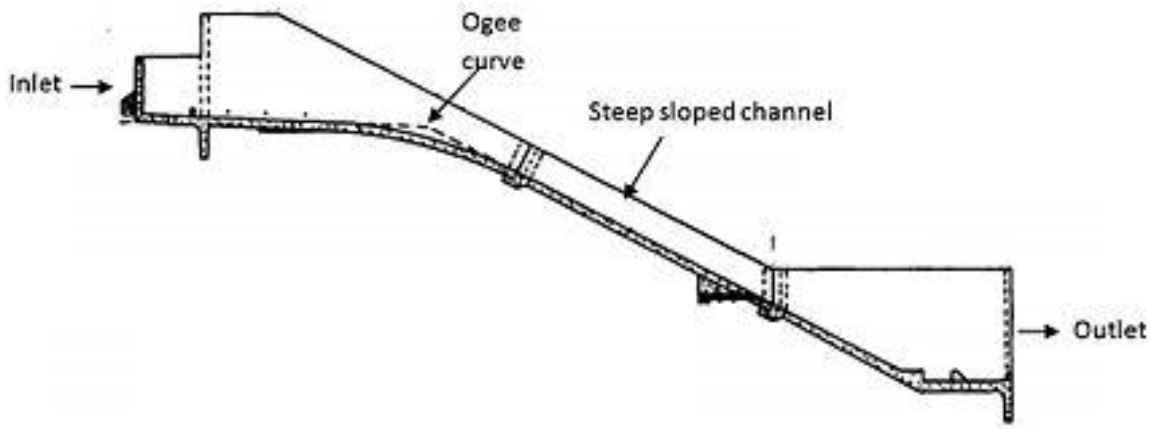

Figure 2.2 Chute Spillway (Beauchamp, K.H., 2014)

Another outfall structure is a culvert, which is shown in Figure 2.2. A culvert is a structure that allows water to flow under a road, railroad, trail or similar obstructions from one side to the other side. Typically embedded so as to be surrounded by soil, a culvert may be made from a pipe, reinforced concrete or other material. Culverts come in many sizes and shapes including round, flat-bottomed and box-like constructions.

Figure 3.2 Culvert (Wikimedia, 2011)

Construction or installation at a culvert site generally results in disturbance of the site soil, stream banks or streambed and can result in the occurrence of unwanted problems such as scour holes adjacent to the culvert structure. According to the observation reported by Keeley there are two general types of erosion downstream from a culvert, either gully scour or a scour hole (Bohan, J.P., 1970). Distinction between the two conditions is made due to the existing slope of the channel, as it is shown in Figure 2.3.

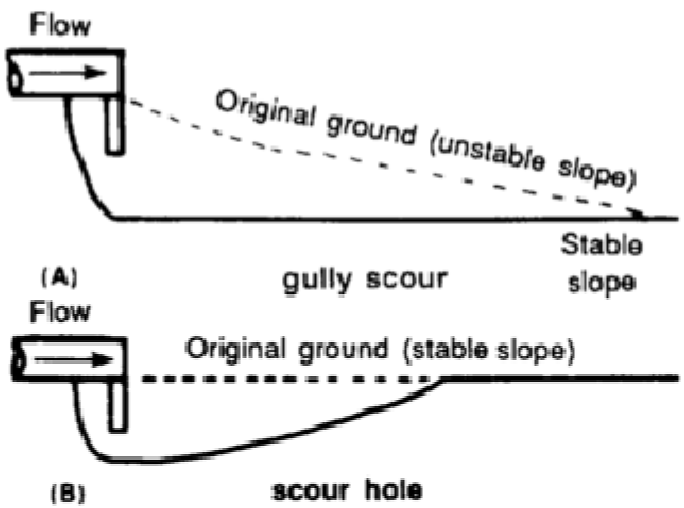

Figure 2.4 Gully scour and scour hole (Bohan, J.P., 1970)

The levels of erosion downstream of the culvert make clear that there is a need for protection (block mattresses), in order to keep the culvert safe. Hence, if measures for protection against scour are not taken, sections of the culvert are in danger, leading to the general instability of the structure.

As it was mentioned above, weirs are another example of structures that need protection against erosion downstream. Generally, a weir is a barrier across a river designed to alter its flow characteristics. Weirs are commonly used in rivers to prevent flooding, measure discharge and help to make rivers navigable. There are several types of weirs like v-notch weirs, broad-crested and sharp crested weirs. In Figure 2.4 a sharp crested weir is presented.

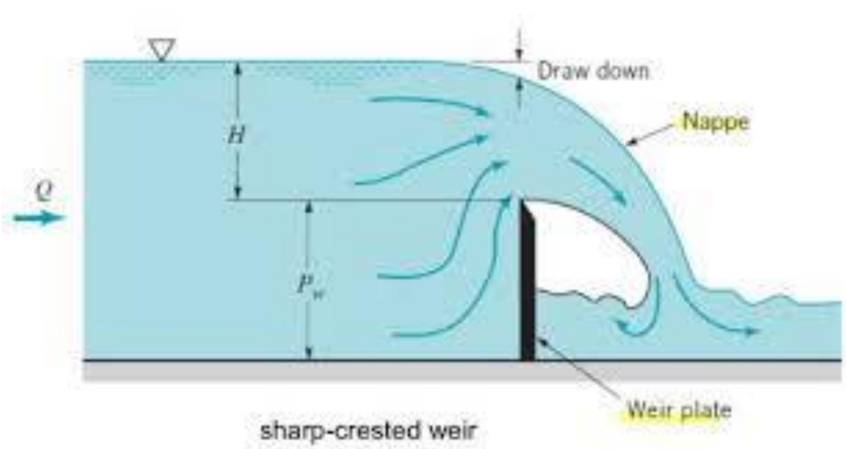

Figure 2.5 Sharp-crested weir (Prycel, M., 2016)

Sharp-crested weirs show some interesting characteristics regarding the flow downstream. Firstly, as it can be observed in Figure 2.4, there is an impact point (in almost the vertical direction) between the flow and the bed. At this point thereafter measures for protection against erosion should be taken. In addition, behind this point a recirculation zone can be noticed. The whole area (impact point and recirculation zone) is governed by high turbulence, which increases the requirements for protection.

Another characteristic type of weir is the gated weir which is shown in Figure 2.5. The gate is used to control water levels and flow rates in rivers and canals. From a hydraulic point of view gated weirs are very interesting, since a transition from supercritical flow to subcritical flow is observed. This transition is achieved by the hydraulic jump, in which energy is dissipated and the levels of turbulence are very high. The last reasons render the bed protection downstream of the gate extremely important.

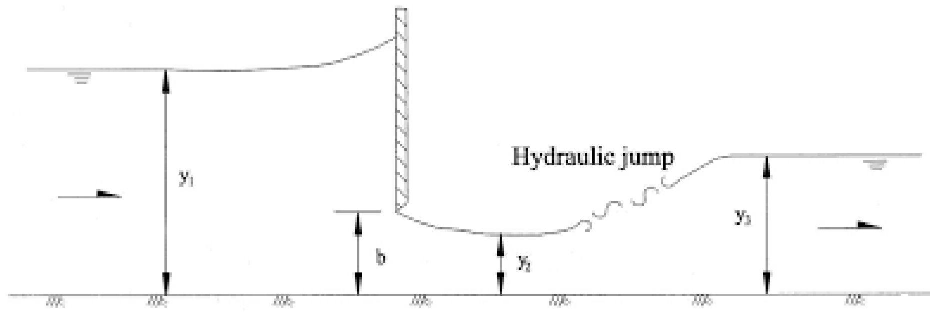

Figure 2.6 Gated weir

Finally, a case with a backward facing step is analysed (Figure 2.6). The vertical expansion, as it is also called, is very interesting, because there is a deceleration zone, a recirculation zone and a mixing layer downstream of it. Special attention should be paid in the reattachment point which is located at distance 6h downstream of the step if h is the height of the step. The area close to the reattachment point appears to need the heaviest bed protection due to the increased turbulence which prevails there.

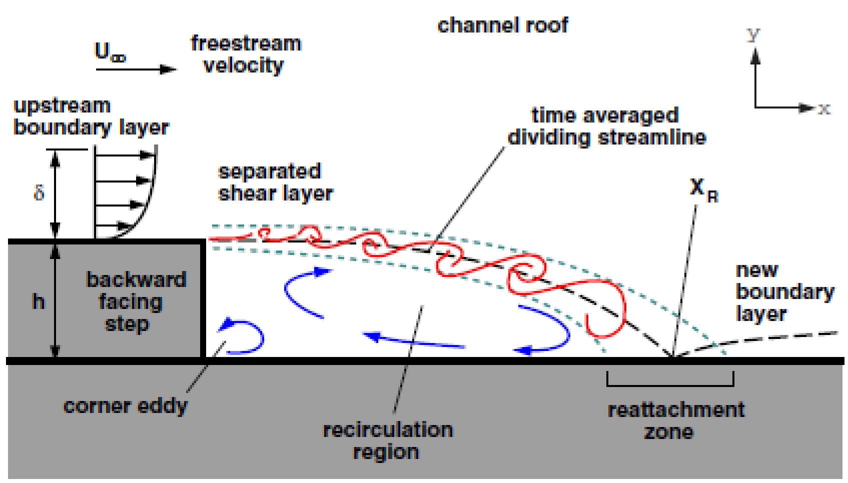

Figure 2.7 Backward facing step (vertical expansion) (Saleel, C.A., 2013)

As it is concluded, the common point of all the aforementioned structures is that they require heavy bed protection against erosion (scour) downstream.

2.2 Block mattresses

Nowadays, block mattresses or block mats are increasingly applied as protection in structures like those reported above. The easy and quick installation (placement) of block mats, which is one of the most important advantages that they have, places them in a dominant position in the market of protection systems. Therefore, the analysis of their characteristics and behaviour appears to be of major importance.

First of all, as block mattress is referred the system of protection, in which individual concrete blocks are placed and connected to a mat (geotextile) usually with plastic pins. HOLCIM which is a major supplier of placed block revetment systems and block mats (betomat) produce them in two different ways:

A) The first way, which is used for smaller (lighter) block mats, contains the separate production of the concrete blocks from a block machine. These blocks are produced with a hole in each corner (in total four holes for a block), where pins are later placed. After the production of the blocks, they are placed in a geotextile and plastic pins are used to connect them and construct the mat. In Figures 2.7, 2.8 and 2.9 the steps of the production are presented.

Figure 2.7 Concrete blocks

Figure 2.8 Placing plastic pins to connect the blocks with the geotextile

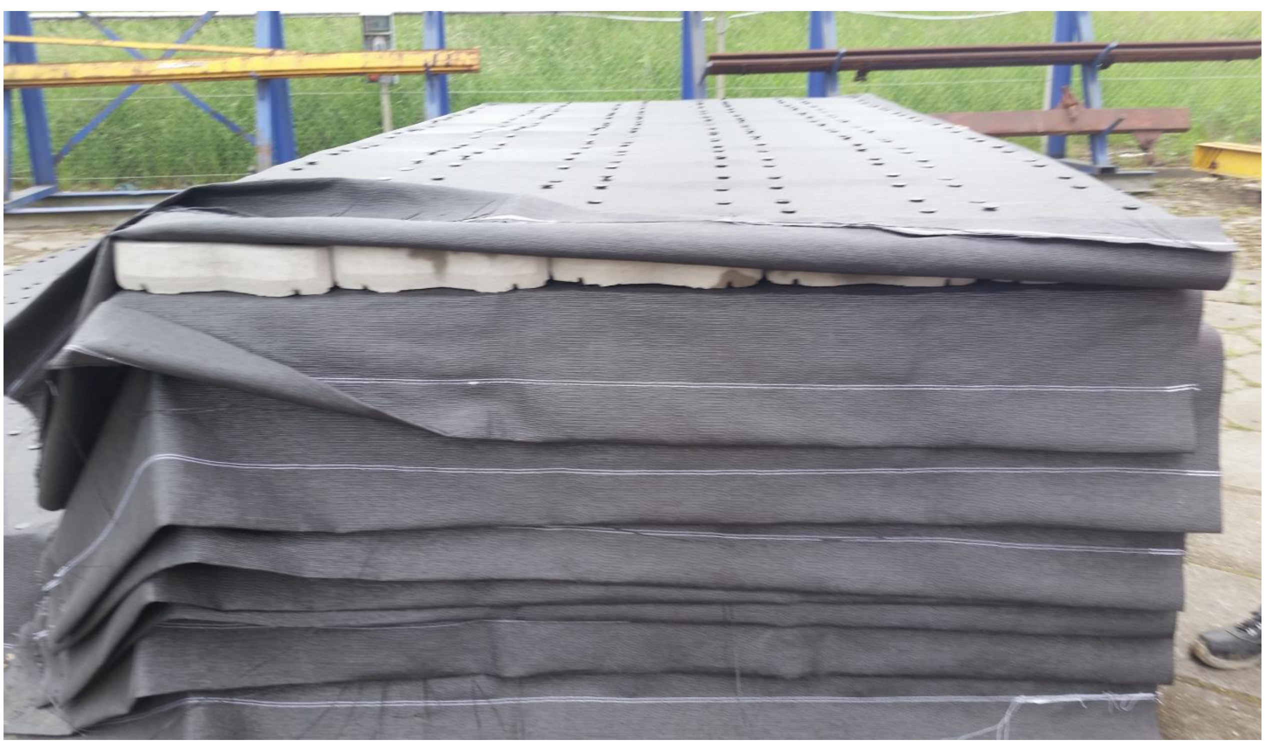

Figure 2.9 Block mattresses ready for installation

B) The second method regards to the heavier (thicker) block mats. In this case the geotextile is placed in an area, a mold for the concrete blocks is placed above and concrete is casted right on the geotextile. In this way a connection between the blocks and the geotextile is achieved without using plastic pins. Figures 2.10 and 2.11 show the molds and the block mats respectively.

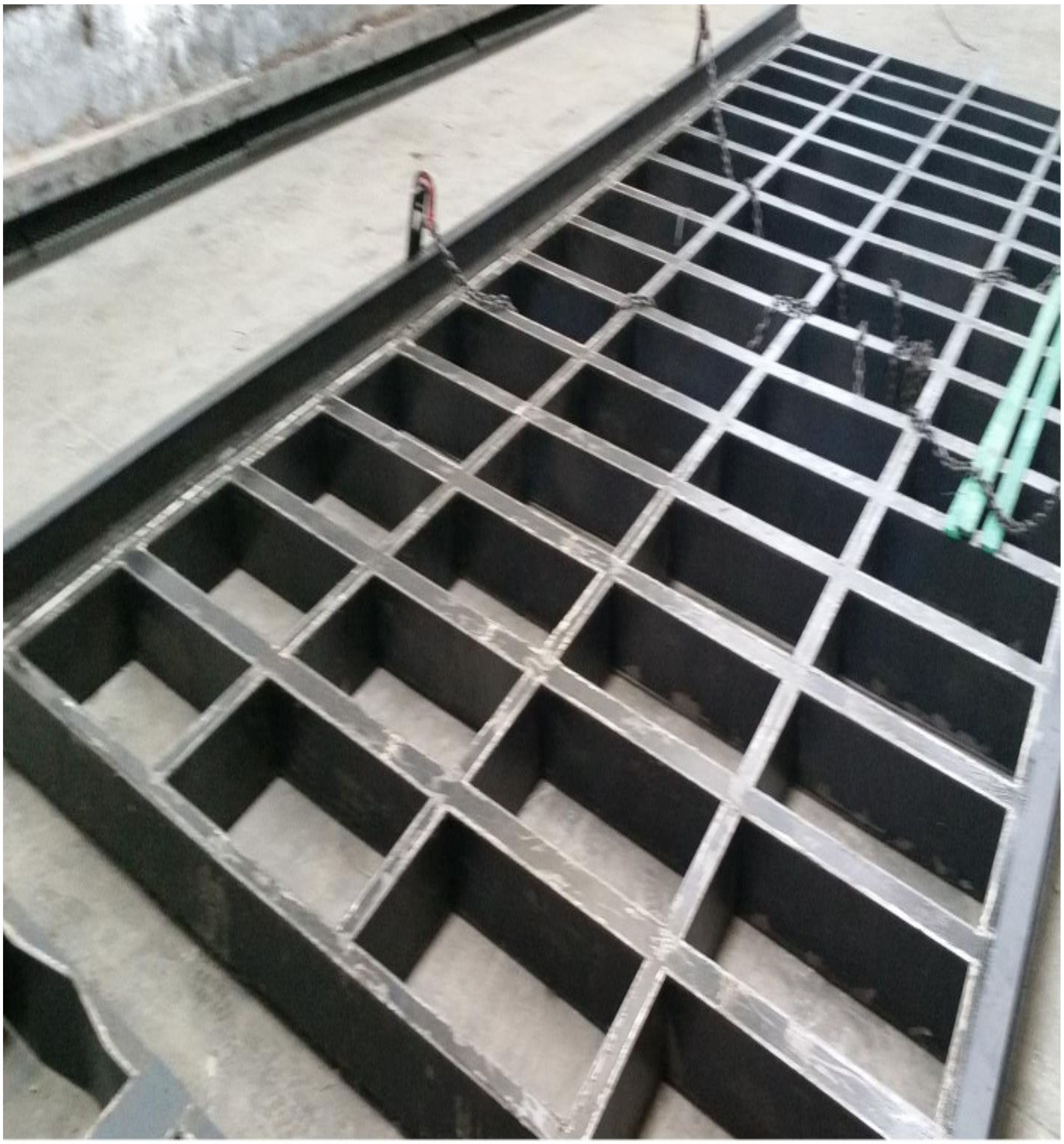

Figure 2.10 Molds for concrete blocks

Figure 2.11 Block mats

The normal length of the concrete blocks is between 30 to 44 cm and the width is 33 to 60 cm. Hence, the maximum dimensions of a block mat are usually 2.40 m (width) x 6.00 m (length). The standard way to apply block mats is presented in Figures 2.12 and 2.13. As it can be observed, the flow is hitting the biggest dimension of the concrete blocks (the smallest dimension (width) of the block mat).

Figure 2.12 Installation of block mattresses (Holcim)

Figure 2.13 Direction of placed block mats (Holcim)

Block mattresses are preferred as protection system in comparison with individual placed blocks or rip rap due to the following advantages (Pilarczyk, K.W., 1998):

A) The easy and quick installation, due to their property of being able to be laid quickly and efficiently even under water.
B) The enhanced stability that they have, due to the fact that a single block cannot move without moving other nearby blocks (all blocks are attached to the geotextile).

Apart from concrete blocks, the geotextile plays a very important role in the general behaviour of a block mat. Many of their characteristics are analysed in (Pilarczyk, K.W., 2000). Indicatively, the basic functions of a geotextile are filtration, separation, protection and waterproofing. In addition, geotextiles are divided in two main categories: 1) woven and 2) non-woven. The main difference between these two categories is that woven geotextiles have increased strength and can perform reinforcing functions in contrast with non-woven geotextiles. The importance of long-term behaviour and durability of geotextiles should be taken into account, because their properties may change by means of alteration in time, fatigue, creep, mechanical damage and biological attack. Usually a geotextile is chosen on the basis of the functional requirements of a project. These requirements are frequently the following:

- Basic material, specific gravity etc.
- Thickness
- Flexibility
- Tensile strength
- Tear strength
- Pore size and open area percentage
- Permeability

- UV light resistance

The multiple requirements of a project may lead to a ‘composite’ geotextile in order to fulfil all of them. Regarding the strength and stability of the geotextiles there are two main reasons that can downgrade the quality and the functions of a geotextile. These are ‘blocking’ and ‘clogging’. Specifically, geotextiles are sensitive to these ‘forms of damage’, which exist when particles of the subsoil block the openings of the geotextile. As a result of this process the water permeability can be reduced to unacceptable levels, which can be disastrous for the structure (protection system). In Figure 2.14 a geotextile which is used for block mats is shown.

Figure 2.14 Geotextile

Despite the fact that block mattresses have a lot of advantages compared to other protection systems, it is of major importance to report and investigate the basic failure modes and the reasons that may lead to instability of this protection system.

First of all, the general critical failure modes are the following:

- Lifting
- Bending
- Deformation
- Sliding

In particular, the failure mechanisms that are observed and reported with the reasons which cause them are listed below (CUR, 1990):

- Lifting up of the block mat, due to uplift forces caused by large head (pressure) difference.
- Loosening of the connection between two adjacent mat sections as a result of the increasing forces when the mat is lifted up.
- Turning over of mat ends due to drag force of the flow.
- Sliding down of the mat due to anchoring failure (areas with slope).
- Bobbing up (move up and down/floating) of the mats if there is a lifted section.
- Possible tear of the geotextile due to rocking of the blocks or contact with foreign 'bodies'.

Taking into account all the above-mentioned critical failure mechanisms, it is concluded that the weakest points are the transitions between two adjacent mat sections and the edges (end) of the block mattress. The transitions between two consecutive mat sections are also called closed edges and the end of the block mat is the open edge. In general, as Pilarczyk, K.W., 1998, reported the weakness of a block mat is an edge. Hence, if mats are not joined together, the edges may turn back. As a result the stability in this case is hardly larger than that of separate stones. A rule for placing the block mat for those reasons clarifies that the installation of block mats should be done so that the gap between the blocks of adjoining mats should nowhere be more than 3 cm (preferably 1 to 2 cm).

In addition, scale model tests that were done by Van Velzen and De Jong (2015) in order to bridge the knowledge gap for the stability of block mats under propeller induced loads demonstrated some very interesting results. Specifically, the failure modes that were checked were:

- Mat bulges (centre) (lifting of the mat at the centre)
- Mat flaps (edge) (turning over of the mat at the edges)

The model tests showed that the stability of a mattress is very sensitive to the placement of the mattress and a possible unfavourable position of the edge blocks. Particularly, the results testified that placing the end of one mat (last row of block) on the geotextile of the next mat is the best way to create a transition, because the gap between the mats is reduced and the blocks in transition are joined together. This method of installation proved to be more stable and smooth than just arraying the mat sections one after the other. In addition, the failure process was proved to be a snowball effect, which means that an initial small uplift of the edge of the mattress is followed by an increase in the drag force acting on the blocks (this process grows continuously with bigger uplift and drag force) leading eventually to the instability-movement of the entire block mat. On the other hand, results showed confusing things about the current design guidelines and reality. The problem was that sometimes results agree well with guidelines, sometimes (closed edges) are conservative and other times (open edge) failure occurred at lower velocities than predicted. Therefore, according to the results, guidelines over predict the required thickness for closed edges and under predict the required thickness for open edges. The stability relation that was used for these test series was Pilarczyk's stability formula for block mats under flow conditions (parameters of this formula (Eq. 2.2) are analysed later in this chapter). Finally, regarding the scale model tests another parameter which is of major importance is the reduction of the scale effects, that are related to the downscaling of the situation. The most interesting and important scale effects, which need innovative ideas in order to be approached and dealt with, regarding the stability of block mats under flow conditions are:

- Increased stiffness of geotextile in scale model
- Permeability of geotextile (a bit small leading to easier lifted edge)

In particular, with respect to the dimensions of the prototype scale mat, the geotextile is considered to be very flexible. However, when a similar is applied in scale model tests, it is considered to be very stiff. Hence, the most flexible and appropriate geotextile has to be used, because stiffness helps against the turning over of the mat, which leads to inaccurate results. The permeability, also, of the geotextile cannot be scaled exactly. For that reason, the most conservative approach should be preferred, which is the less permeable geotextile (allow the mat to be lifted (fail) easier).

2.3 Existing formulas

According to the Rock Manual 2007, regarding the flow conditions there are three basic stability formulas that have been suggested and most of them are only suitable for rip-rap protection. Generally, the three stability formulas used for current attack are: Pilarczyk's (1995), Escarameia's and May's (1992) and Maynord's (1993). The relation of each formula is presented below.

First of all, the formula of Escarameia and May (1992) is presented which is a form of the Izbash equation, in which the effects of turbulence are totally considered and quantified:

$$\frac{u_b^2/2g}{\Delta * D_{n50}} = \frac{1}{c_T} \qquad (2.1)$$

It is clearly observed that this equation gives the relationship between the median armourstone size (D_{n50}) and the hydraulic parameters. The fact that this relation provides values for median nominal diameter and not for thicknesses of block elements makes this formula more relevant to rip rap protection than block mats. It is worth mentioning, though, that this formula is very useful in situations like downstream of hydraulic structures (gates, weirs, spillways, culverts) which are considered in this thesis. The following table (Table 2.1) contains some characteristic values for the turbulence coefficient c_T, as they are presented in the Rock Manual 2007.

• armourstone	valid for r≥0.05
	c_T=12.3 r=0.20
• gabion mattresses	valid for r≥0.15
	c_T=12.3 r=1.65

Table 2.1 Design guidance for turbulence coefficient c_T

Secondly, the empirical relation of Pilarczyk (1995) is:

$$\frac{U^2/2g}{\Delta * D} = \frac{\psi_{cr}}{\varphi_{sc} * 0.035} \frac{k_{sl} * k_t^{-2} * k_h^{-1}}{1} \tag{2.2}$$

Specifically, Pilarczyk elaborated the formula of Escarameia and May, which contains only one parameter for turbulence and added several other parameters like: 1)ψ_{cr} which is the mobility parameter and is similar to Shields parameter, 2)ϕ_{sc} which is a stability factor, 3)k_t which is a turbulence factor, 4)k_h which is a velocity profile factor and 5)k_{sl} which is a side slope factor. A noteworthy observation has to do with the ratio 0.035/ψ_{cr} which compares the stability of the system to the critical Shields value of loose stones which is used as reference. In the table below (Table 2.2) design guidance for the parameters in PIlarczyk's formula is presented.

Mobility parameter ψ_{cr}	• rip rap and armourstone: 0.035
	• box gabion and gabion mattresses: 0.070
	• rock fill in gabions: <0.100
Stability factor ϕ_{sc}	• exposed edges of gabions: 1.0
	• exposed edges of rip rap: 1.5
	• continuous rock protection: 0.75
	• interlocked blocks and block mats: 0.5
Turbulence factor k_t	• normal turbulence level: k_t^2=1.0
	• non uniform flow, increased turb.: k_t^2=1.5
	• non uniform flow, sharp bends: k_t^2=2.0
	• non uniform flow special cases: k_t^2>2
Velocity profile factor k_h	• fully developed logarithmic velocity profile
	$k_h = 2/(\log\left(1+\frac{12h}{k_s}\right)^2)$ k_s=1 to 3D_{n50} and for shallow rough flow k_h=1
	• not fully developed velocity profile
	$k_h = (1+\frac{h}{D})^{-0.2}$
Side slope factor k_{sl}	$k_{sl} = k_d * k_j$
	$k_d = (1-(\sin^2 a\, /\, \sin^2 \varphi_{ar}))^{0.5}$, α: side slope angle
	$k_j = \sin(\varphi_{ar} - \beta)/\sin\varphi_{ar}$, β: slope angle longit. dir.

Table 2.2 Design guidance for the parameters in PIlarczyk's formula

The third formula that was developed by Maynord (1993) is a stability formula for rip rap and armourstone that is not based on the threshold of movement criterion, in which both Pilarczyk and Escarameia and May were based. Specifically, it takes into account the thickness of the stone layer, in the basis of not allowing the protected material to be exposed. The characteristic stone sieve size (D_{50}) is determined as follows:

$$D_{50} = f_g^{0.32} S_f C_{st} C_v C_T h (\frac{U}{\sqrt{\Delta} * \sqrt{k_{sl} g h}})^{2.5} \tag{2.3}$$

Some characteristic values for the parameters that are included in Eq. 2.3 are presented in Table 2.3.

Safety factor S_f	minimum value S_f=1.1
Stability coefficient C_{st}	angular armourstone C_{st}=0.3
	rounded armourstone C_{st}=0.375
Velocity distribution coefficient C_v	straight channels, inner bends C_v=1.0
	downstream of concrete structures C_v =1.25
Blanket thickness coefficient C_T	standard design C_T=1.0
Side slope factor k_{sl}	$k_{sl} = -0.67 + 1.49 \cot a - 0.45 \cot^2 a + 0.045 \cot^3 a$
	α= slope angle of the bank to the horizontal

Table 2.3 Design guidance for the parameters in Maynord's formula

Among the three formulas that were presented, usually, the Pilarczyk's empirical relation is used in order to determine the stability of block mattresses. The reasons that lead to the use of this specific formula are analysed below. Firstly, PIlarczyk's formula is the only one that contains values for parameters when block mattresses are applied (and generally block elements). Both the other two relations consider rip rap as the basic material of protection. In addition, another noteworthy observation has to do with the levels of turbulence and how each method quantifies them. In normal levels of flow turbulence all of the suggested relations give fairly comparable results, but when the levels of turbulence increase considerably, Escarameia and May tends to give more conservative results leading to larger armourstone sizes. Maynord's formula cannot actually take into account high levels of turbulence since the velocity distribution coefficient is increased to 1.25 for situations such as flow downstream of structures, but this is not adequate for extreme situations. Applications of block mattresses as bed protection have shown that considerably turbulent situations need to be treated, which means that Maynord's formula is not a good solution for this case. Moreover, the Eq. 2.1 of Escarameia and May was derived with the objective of characterizing the effect of turbulence on armourstone stability. Therefore, it can be argued if this equation can lead to a safe design in very turbulent situations because of the absence of field data.

All the aforementioned reasons make clear that Pilarczyk's formula is the most suitable, in order to determine the stability of block mattresses under flow conditions. Although, there is definitely a need to 'optimise' this formula, since it contains both Izbash and Shields characteristics. As a result, the corresponding formula is more generic and gives the impression that potentially can cover a larger range of applications, leading to conservative or frequently to inaccurate results. One crucial factor that needs to be taken into account during this research for the optimization of Pilarczyk's formula is the fact that the relation of Escarameia and May is very useful in situations like downstream of hydraulic structures (weirs, gates, spillways, culverts) which is the area that it is considered to be protected by block mattresses in this master thesis. Hence, a relation or connection between these two formulas should be investigated (since Pilarczyk elaborated the formula of Escarameia and May).

2.4 Synopsis

Objective of this research is to get insight in the physical processes which cause damage to the block mats and the optimisation of their stability under flow conditions. As referred above scope is to determine the stability of block mattresses at the end of outfall structures (like culverts or weirs). The range of velocities, that are representative for these types of structures, is usually between 1 m/sec to 3 m/sec, but sometimes velocities reach magnitudes of 5 m/sec too. In Figures 2.12 and 2.13, it is clearly observed that the transition from one mat section to the other is made (according to the design characteristics) to be along (parallel to) the flow direction, as there is a maximum width (around 2.50 m) for the produced block mats. In cases, though, that the protected area is very large, it is possible to have both horizontal and vertical transitions. The dominant stability relation, that is used, is the Pilarczyk's stability formula. However, this formula needs to be optimised, especially, for block mats, because it leads sometimes to inaccurate results. This formula, characteristically, does not distinguish between open (end) and closed mattresses (transition), which proves the fact that it requires optimisation, considering that these parts are the weakest points and need to be well-designed. In addition, considering the fact that Pilarczyk's relation would give the same required block thickness for the four different cases (culvert, sharp-crested weir, gated weir and backward facing step) of this research makes clear that a better understanding of the parameters, that are obtained, is required.

The aforementioned reasons make clear that scale model tests are needed, in which the stability of the block mattresses will be tested. These tests are required to optimise parameters (turbulence, open or closed edges, threshold of motion) of the existing design method regarding outfall structures. Consequently, there is a need to describe better the loads and at the same time improve the strength of the system. In addition, the most unfavourable and the most favourable configuration of the mattresses need to be checked and how each configuration contributes to the stability, since the stability of the mattresses is strongly dependent on their formation during installation. Furthermore, the shape/weight/thickness of the first row blocks needs to be tested, as it seems more critical compared to the block thickness of all blocks.

3. Study area – Approaching method

As it is specified by the chapter of literature review, the stability formula which is used for the design of block mats is Pilarczyk's empirical relation (described in Equation 2.2). Study area of this research is to delve into the main characteristics and parameters of this formula, which will potentially lead to a better use and application of this relation in the design of protection systems that are required downstream of hydraulic structures (four cases as described previously). Moreover, in this chapter the available approaching methods are described, from which the most suitable is selected.

3.1 Load parameters

First of all, the loads and the load parameters of Equation 2.2 should be determined and analysed. In particular, PIlarczyk's stability relation contains the following load parameters:

- $U^2/2g$ (velocity head)
- k_{sl} (side slope factor)
- k_t^2 (turbulence factor)
- k_h (velocity profile factor)

The term of velocity head $U^2/2g$ is an Izbash characteristic, which means that the velocity near the bed needs to be determined in order to be used in this formula. However, an Izbash based relation looks explicitly to individual rocks or grains, which is not so useful for mattresses, considering the connection between the blocks. On the other hand, Izbash formulas are used especially in cases of non-uniform flow and are extremely useful in situations like downstream of hydraulic structures (such as the four cases that are described in this master thesis). Regarding the other three k (load) parameters, there is an extensive analysis of their values in Table 2.2. These factors and most of their values are empirical, which verifies the need for measurements and tests in order to have a more accurate design equation. Specifically, for instance the turbulence factor can be between 1 and 4 (or even more), which is not 'acceptable' for a coefficient, since coefficients are considered to have values around 1. Moreover, the velocity profile factor is a coefficient that was created in order to cover the possibility of a non-developed velocity profile near transitions which leads to higher velocities near bed. In this case, the degree that this parameter affects the required block thickness needs to be investigated (and if there is a way to be omitted by creating a 'smooth' transition). Thereafter, a better description and understanding of all the aforementioned load parameters is required.

3.2 Strength parameters

Apart from the loads and the load coefficients, there are, also, strength parameters (resistance 'forces'). Particularly, Pilarczyk's stability formula contains the following strength parameters:

- $\Delta * D$
- $\frac{\psi_{cr}}{\varphi_{sc}*0.035}$

The term $\Delta * D$ refers to the required block thickness and the general characteristics (like density) of the blocks. It is understandable that the protection system can deal with more severe conditions (higher velocities) by increasing the value of this term. The second term ($\frac{\psi_{cr}}{\varphi_{sc}*0.035}$) is of significant interest, because it is mainly the one that needs further investigation. Specifically, 0.035 as reported by Pilarczyk, K.W., 2000, is chosen as a reference value for a critical shear stress parameter (mostly between 0.03 and 0.04 for a rock) and ϕ_{sc} is used due to the lack (scarcity) of prototype data on the stability of protection systems under current attack. The factor ψ_{cr} is definitely a Shields parameter (stability parameter), which means that the use (validity) of this parameter demands a uniform flow. This comes in contradiction with the Izbash parameter defined in the load parameters. In addition, the stability factor ϕ_{sc} is chosen between 0.5 and 1.5 with lower values when the system has higher integrity (in edges and transitions higher values of ϕ_{sc} are expected). Although, the lack of data as mentioned above and the fact that most of these values are empirical highlights the necessity of tests and measurements. All the aforementioned characteristics should be taken into account in order to choose the most suitable way to deal with the stability of block mats.

3.3 Methods of approach

The methods of approach that are used in order to deal with the stability of a protection system are the following:

- Evaluation of past experience (if there are past tests that have taken place, the data of these tests can be used in the validation or even the optimisation of a stability formula)
- On-site investigations on existing structures or large scale model tests (usually very costly considering the equipment for measurements and the facilities that are needed)
- Calculations and mathematical models (always useful and can be combined with other approaching methods)
- Experiments and small scale model tests (usually in cases when there are not available data in order to get some from measurements)

3.4 Selection of approaching method

The first option is to derive a new stability parameter for block mats using available data. Specifically, the use of data from the recent scale model tests on the stability of block mats under propeller induced loads (which were mentioned and described in the second chapter) that were done in Deltares by (Van Velzen, G., De Jong, M.P.C., 2015) could be a reasonable first approach in order to check combinations of velocity and turbulence that lead to failure. Stability parameters are usually expressed in the form of dimensionless relation between hydraulic load and bed strength (ratio between destabilising forces and resistance forces).

The flow forces that may lead to instability of the protection system are:

- Drag force

- Shear force
- Lift force

All these forces are proportional to the term $\rho u^2 d^2$, where ρ is the water's density and d is the stone diameter (in case of stones). On the other hand the force that resists to the movement is:

- Gravity

Gravity force is proportional to the term $(\rho_s-\rho)gV$, where ρ_s is the stone's density and V the volume of the stone (in case of stones). In that case a general form of a stability parameter could be:

$$\Psi = \frac{u^2}{\Delta g d} \tag{3.1}$$

In cases of uniform flow this parameter is a very good approach for loose stones (as protection), as Shields observed in 1936. However, in cases of non-uniform flow near hydraulic structures, turbulence needs to be taken into account.

In these situations:

$$u = \bar{u} + \acute{u} \tag{3.2}$$

Where $\bar{u}$ is the mean flow velocity and $\acute{u}$ the values of the fluctuations. Consequently,

$$\overline{u^2} \neq \bar{u}^{\,2} \tag{3.3}$$

But,

$$\overline{u^2} = \overline{(\bar{u} + \acute{u})^2} = \bar{u}^{\,2} + 2\overline{u\acute{u}} \tag{3.4}$$

In that case, Equation 3.1 is transformed into:

$$\Psi = \frac{\bar{u}^2 + 2\,\overline{u\acute{u}}}{\Delta g d} \tag{3.5}$$

In fact, this stability parameter includes the effect of turbulence, but there is a limitation that is required in order to be used. This limitation has to do with the magnitude of average velocity and specifically $\bar{u} \gg \acute{u}$. Moreover, the above mentioned stability parameter, is characterised by the measurement or application of the velocity and turbulence at one and only specific point above bed (and not like a depth-averaged value). On the one hand, this makes the stability parameter extremely easy to use, but on the other hand it is difficult to determine the exact point above bed, where the velocity and turbulence should be known.

The following stability parameters provide a spatial average over distance above bed where velocity and turbulence should be known. Typical examples of these stability parameters for loose stones under stationary non-uniform flows are:

- Jongeling (2003)

$$\Psi_{WL} = \frac{\langle(\bar{u} + \alpha\sqrt{k})^2\rangle_{hm}}{\Delta g d} \tag{3.6}$$

Where, α is an empirical turbulence magnification factor, k represents the turbulence kinetic energy and $\langle ... \rangle_{hm}$ is a spatial average over a distance of hm= 5d+0.2h above the bed (h=local water depth).

- Hofland (2005)

$$\Psi_{Lm} = \frac{max\left[\langle\bar{u} + \alpha\sqrt{k}\rangle_{Lm}\frac{L_m}{z}\right]^2}{\Delta g d} \tag{3.7}$$

Where, $Lm = \kappa z\sqrt{1 - \frac{z}{h}}$ denotes the Bakhmetev mixing length and z the height above the bed (κ=Von Karman constant).

- Steenstra (2016)

$$\frac{\psi^*_{new}}{C_b} = \frac{\left(max\left[\langle\bar{u} + \alpha\sqrt{k}\rangle_{Lm}\frac{L_m}{z}\right]^2\right) - \frac{C_m}{C_b}\frac{dp}{dx}d}{K_\beta \Delta g d} \tag{3.8}$$

Where, Kβ is the correction for the bed slope, Cb is the bulk coefficient (force caused by velocity and turbulent velocity fluctuations), Cm is the added mass coefficient (force caused by pressure gradient) and dp/dx is the pressure gradient.

All these formulas were created according to data from measurements (and the empirical parameters like α were determined). The next step was to relate the stability parameter with the bed response (damage). For stones the bed response can be considered in two different ways:

- Entrainment rate (number of pick-ups per time and area)
- Bed load transport (number of particles transported through a cross-section per unit time)

So, the result is a relation between the bed response either as entrainment rate or as bed load transport and the stability parameter in the form of Equation 3.9:

$$\Phi = f(\Psi) \tag{3.9}$$

However, for non-uniform flows entrainment rate is preferred because stability parameters are local parameters and entrainment rate is also dependent on local parameters, whereas bed load transport is more dependent on upstream hydraulics (so non-local).

Hence, in the case of block mats after evaluating the data (and the creation of a stability parameter) the next step should be a relation to link the damage on the block mats with the forces that act on them. Nevertheless, there is no way to link the damage on the block mats like the way it is done on stones, as the basic failure mechanisms have to do with the overturning of the block mat at the edges or the transitions. Consequently, the stability parameter, when dealing with block mats, should determine if they are stable or unstable. This means that under certain circumstances (type of flow, structures, block thickness, etc.) there should be a specific value of the stability parameter, for which the block mat is unstable and fails (also every value larger than this critical value of the stability parameter leads to failure).

Unfortunately, this option (1st option of approaching methods) is not possible to be selected due to the lack of data in the area (field) of interest. Specifically, in order to create a stability parameter like the ones presented above, it is necessary to have measurements about velocities and turbulence intensities in the area of interest, which in this case is right above the edge of the block mat. However, in the recent scale model tests on the stability of block mats under propeller induced loads, all the measurements that were taken about velocities and turbulence were due to the propeller and at the spot of the propeller (Van Velzen, G., De Jong, M.P.C., 2015). So, there is not analysis of the spread of turbulence at block mats. Therefore, there is no way (reliable) to relate these measurements at the propeller with the ones that are required right above the block mat (at the edge). However, in the report of the aforementioned scale model tests there is a relation with which the expected velocity near the block mats can be estimated. Particularly, in the following equations the way to estimate near bed velocity is described. The methodology to estimate near mat velocities has to do with the measurements of the rotational speed (n) of the propeller during failure and the calculation, using a linear function, of the outflow velocity (U_0)(Eq.3.10). Then, this outflow velocity is used to estimate the velocity (u_b)(Eq.3.11) near bed (where block mats are applied).

$$U_0 = 0.175n + 0.014 \tag{3.10}$$

$$u_b = 0.306U_0\frac{D_p}{h_p} \tag{3.11}$$

Where,

D_p is the effective diameter of the propeller (=diameter of the propeller for ducted propellers)

h_p is the distance between the bed and the axis of the propeller (h_p =1.5D_p or 2D_p as these two heights above bed of the propeller were examined)

According to the outflow velocities (result of tests) that led to failure, which are 8.4 m/sec for closed edges and 3.4 m/sec for open edges, an estimation of the expected near bed velocities can be made using Equation 3.11. These values are presented in Table 2 for both closed and open edges.

Closed edge		Open edge	
Outflow velocity (m/sec)	Expected near bed velocity (m/sec) for h_p=1.5D_p	Outflow velocity (m/sec)	Expected near bed velocity (m/sec) for h_p=1.5D_p
8.4	1.71	3.4	0.69

Table 3.1 Expected near bed velocities

In contrast with the estimation of the expected near bed velocity using the outflow velocity near the propeller (described above), it is not so simple to make estimations for the expected turbulence intensities near the block mats. Specifically, in the scale model tests on the stability of block mats under propeller induced loads there was no estimation of turbulence intensities at the bed, but the values that are presented in The Rock Manual 2007 were assumed. In that way, estimation for turbulence intensities can be made regarding the value of the turbulence factor k_t. The recommended value for this factor when dealing with propeller loads is k_t^2=5.2. There is a relation, though, that connects the turbulence factor with the turbulence intensities according to The Rock Manual 2007.

$$k_t = \frac{1 + 3r}{1.3} \tag{3.12}$$

Therefore, taking into account this assumption the expected turbulence intensity is r≈0.65, which is considered to be very high and similar to levels of turbulence that exist downstream of hydraulic structures. However, this value of turbulence intensity is not reliable. Specifically, Figure 3.1 shows the turbulent velocity fluctuations in a propeller wash compared with the fluctuations in a free circular jet.

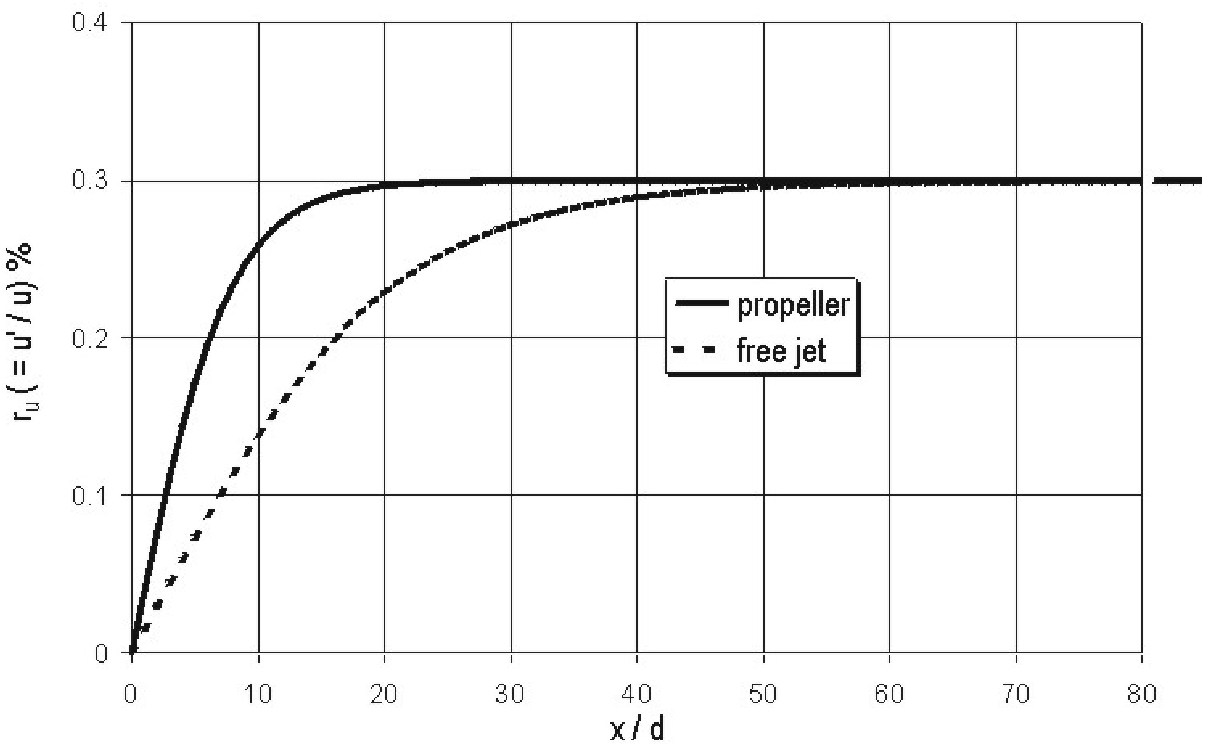

Figure 3.1 Turbulence in propeller wash and free circular jet (from Rijkwaterstaat/DHL (1998))

In addition, as reported by (Verhagen, H.J., 2001) the flow of a propeller jet is very turbulent and relative turbulence may reach values of r≈1.75, which are considered to be extremely high. Hence, the estimation of expected turbulence near block mats is definitely not reliable.

Consequently, the second option in order to deal with the stability of block mats is to make a step back and "produce" all the required data that may lead to the derivation of a stability parameter through the methodology that is described above. This step back contains the performance of an experiment in order to measure all the parameters like velocities, turbulence intensities and their influence on block mats. The best way, therefore, to approach the stability of block mats under flow conditions considering the existent background is to do an experiment.

3.5 Set-up of the experiment (preparation and first thoughts)

In order to organise the set-up of the experiment there are several parameters that need to be determined and examined. First of all, objective of this experiment is to “produce” the required data described in the previous chapter that may lead to a new stability parameter. The aforementioned data have to do with measurements of velocities and turbulence at the edge of block mats. The fact that the influence of turbulence on the stability of block mats is investigated has as consequence the need for specific conditions at corresponding points.

In addition, it is of major importance to analyse the reasons why this experiment is needed and what are the results that are expected to be produced by this experiment. As it was mentioned in the previous paragraph, scope of this experiment is to ‘lead’ to the required data (turbulence intensities, velocities) that will support the derivation of a new stability parameter for block mats, like the ones described previously. This experiment, also, is expected to enhance the knowledge on the role of turbulence on the stability of block mats since there is a lack of information about the reaction and the behaviour of block mattresses which are subjected to turbulent conditions.

One way to approach this problem (role of turbulence) could be to examine the stability of block mats for different values of turbulence intensity and velocity. Particularly, a layer with rough stones can be used in order to increase the levels of turbulence that need to be examined on the block mats. By adding or reducing the bed roughness, these levels of turbulence can be controlled. Consequently, it is possible to get couples of values for turbulence and velocity for which the block mat is not stable and create a diagram in order to present the ‘regions’, where block mats are stable and not stable according to the turbulence-velocity (r-u) values. Each block thickness that will be examined can lead to a different diagram. In that way, it is possible to create a design guideline for specific (thicknesses) block mats like Betomat (Holcim) GS-VB-15. In addition, by finding the minimum values for the combination of r-u at which a specific thickness of a block mat becomes unstable, it is achievable to derive a new stability parameter for block mats by examining different block thicknesses.

In more details about the experiment, as presented in Figure 3.2 that follows, it is important to place a layer of rough stones upstream of the block mat in order to create a turbulent flow. Because of the fact that couples of different values of r-u that lead to instability are sought, the possibility of creating flows with different levels of turbulence needs to be checked at first. This can be achieved by changing the bed roughness upstream of the block mat (place rougher stones etc.). Another way could be by analysing the layer of rough stones as a backward facing step, which means that at the reattachment point (6 or 7 times the height of the step downstream) the maximum turbulence occurs. As a consequence the length of the block mat has to be a little bit smaller like 4 or 5 times the height in order for the edge to be placed at different points downstream of the step including the positioning of the edge in the reattachment point. In that way different velocities and turbulence intensities can be analysed and examined depending on the position of the block mat downstream of the step. After ensuring that different types of flow (less turbulent, more turbulent, etc.) can be examined, the most important part of the experiment will take place which is the observation of the stability of the block mats while measuring the turbulence intensity and the velocity. The next step after the measurements is to 'create' diagrams of r-u (design guideline) and interpret the tendencies that these diagrams show regarding the combinations of mean velocity and turbulence intensity at failure.

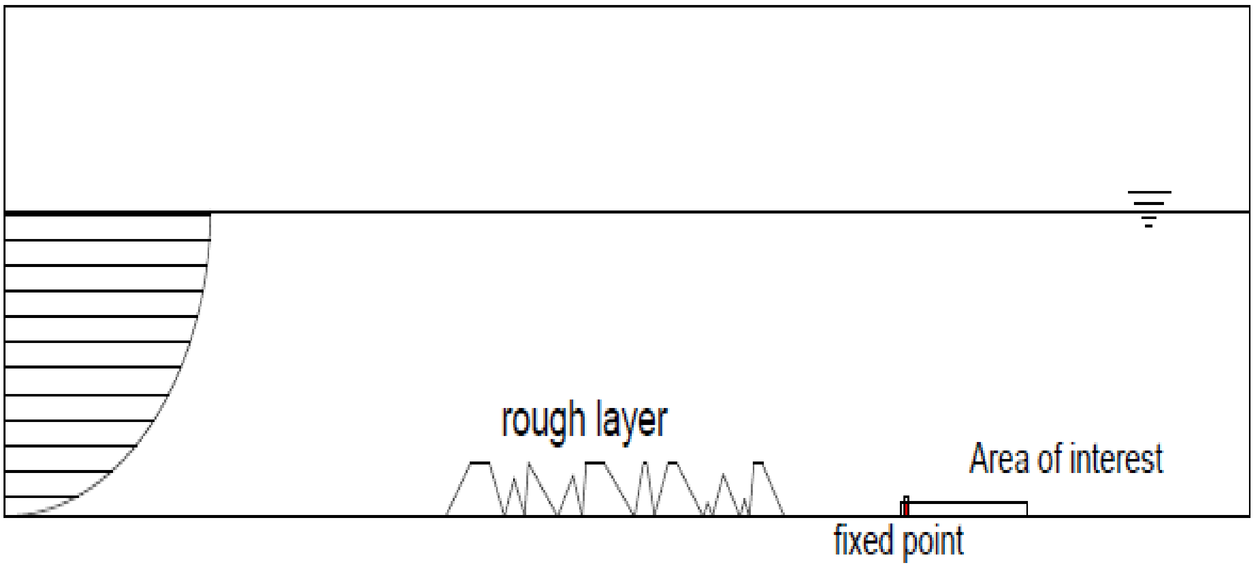

Figure 3.2 Sketch of the flume

The block mats that are chosen to be examined refer to the Betomat (Holcim) GS-VB-15, which were also used in the previous experiments (Van Velzen, G., De Jong, M.P.C., 2015) and have a thickness of 1.9 cm with dimensions circa 0.30x0.80 m^2 (width x length). Consequently, it is of major importance to check if the flumes that are available for tests at the water lab of TU Delft are suitable for this type of experiments.

Figure 3.3 Water flume for experiments under current loads

In the water lab of TU Delft there are three types of flumes, where experiments under current loads can be performed. The differences between these flumes have to do with the dimensions of the flumes. The smallest one that is available has a width of 0.20 m and a maximum height (water depth) of 0.38 m. The flume which is presented in Figure 3.3 has a width of 0.4 m, a maximum height of 0.4 m and a length of 14 m. The maximum discharge, also, of this flume is 60 l/sec. Regarding the biggest flume, the width of it is 0.75 m and the maximum height is 0.80 m.

In order to select the appropriate flume another aspect that needs to be considered is the estimation of the expected 'critical' velocity for the block mats. In that way the possibility of achieving the desired velocity in the water lab is checked. An approach for this estimation can be made by using the empirical relation of Pilarczyk described in Equation 2.2. Specifically, by assuming that k_t^2=1.5 (increased turbulence downstream of structures), ϕ=0.5, ψ=0.07, Δ=1.31, g=10m/sec^2 and **D=1.9 cm in model**, the velocity during failure is expected to be **u_{cr}=1.15 m/sec in model.** Therefore, the 'best' flume for the tests is the second one (presented in Figure 3.3) with width around 0.4 m.

Furthermore, the next step contains the selection of the measurement equipment and the frequency of hydrodynamic measurements. There are five different types of measurement equipment that can be used in order to measure the velocity:

- LDV (Laser Doppler Velocity meter)

The velocity measurement can be performed with an LDV, which has the advantage that it does not interrupt the local flow. A beam of laser light impinging on a moving particle will be partially scattered with a change in wavelength proportional to the particle's speed (the Doppler effect). A LDV focuses a laser beam into a small volume in a flowing fluid containing small particles. The particles scatter the light with a Doppler shift. Analysis of this shifted wavelength can be used to directly and with great precision determine the speed of the particle and thus a close approximation of the fluid velocity. The use of laser, though, makes its use extremely dangerous (certain safety measures need to be taken) and costly.

- PIV (Particle Image Velocimetry)

Aim of the PIV is to visualise the spatial structures in the flow, 'determine' the origin of movement and make multiple simultaneous measurements. In practice, there is a laser sending a very thin beam, which is changed into plain using lenses (it is like making a cross-section in the middle of the flume and eliminating this vertical plain). In that way, you get images of the velocity vectors (every for example tenth of second) and you observe when the protection system (block mats) is lifted or moving. The use of a fixed point (hinge) as described above to prevent block mat from moving away is suggested in order to make measurements and consecutive experiments quickly.

- BIV (Bubble Image Velocimetry)

The BIV is suitable when there is a large aerated region, a large number of bubbles and a large size of bubbles. Specifically, BIV is similar to PIV but it directly correlates the bubble images and does not require a light sheet for illumination (this is the advantage of BIV compared to PIV). So, bubbles are the tracer and bubble velocity is measured by correlating the 'texture' of bubble images. In addition, when there is highly aerated bubbly flow, PIV fails due to the uncontrollable scattering of laser light. Consequently, BIV is the most suitable measurement equipment because it works in high void fraction region and it does not need a laser light sheet, which makes it 'cheaper'.

- ADV (Acoustic Doppler Velocity meter)

ADV is used to obtain velocity components. The original idea is to use the 'Doppler shift' to calculate velocity. The Doppler shift is the observed change of sound pitch as result from relative motion. An example of Doppler effect is the sound made by a vehicle approaches, i.e. a car has a higher pitch as it approaches and lower as it goes away. This change in pitch is proportional to how fast the vehicle is moving. So, the acoustic method for measuring velocity is based on the principle of the Doppler shift, involving the speed of sound. In addition, Doppler shift is the difference between the frequency when there is no movement and the difference when either the target or the source or both are moving. For that reason, if the original frequency and velocity of sound are known, then the frequency change and the along sound (beam) velocity can be measured. Because it is only possible to measure along beam velocity, instruments have 3 or 4 transducers, so that 3 velocity components can be measured.

- EMS (Electromagnetic Flow meter)

EMS is a device measuring the fluid velocity in 2 directions (usually the –x and –y) depending on the way that it is placed in the water. The accuracy and reading error is ±0.02 m/sec. The advantage of this flow meter is that it is very easy to use and there are not important safety rules that need to be followed during the measurements. On the other hand, the disadvantage of an EMS is that it is placed in the water and for that reason it interrupts the flow.

Apart from the measurement equipment that should be chosen, the frequency of the hydrodynamic measurements should be selected too. A reasonable approach would obtain hydrodynamic measurements performed with a frequency of at least 100 Hz, in order to be able to get turbulent properties from the flow velocity signals. Finally, taking into account the fact that this experiment is 'the very first' and may be considered as the first approach for a new field of experiments (on the stability of block mats) an Electromagnetic Flow meter is selected (EMS) with a sampling frequency of 100 Hz.

Finally, the basic points of the experiment, according to a first approach that is described above, are gathered and presented in the following Table 3.2.

Measurement equipment	Frequency of hydrodynamic measurements	Block mat dimensions (length x width)	Block mat thickness	Flume dimensions (length x width x height)
EMS	100 Hz	0.80 x 0.30 m^2	1.9 cm	14 x 0.4 x 0.4 m^3

Table 3.2 Basic points of the experiment

3.6 Scale effects

First of all, it is worth mentioning again that the block mattresses that are tested in the experiments of this Master Thesis project are the same with the ones, which were used for the tests under propeller-induced loads in Deltares (Van Velzen, G., De Jong, M.P.C., 2015).The main properties of the block mattress are:

- Weight and shape of the blocks and the geotextile
- Stiffness of the joints
- Stiffness of the geotextile
- Permeability of the mattress
- Tensile strength of the geotextile

According to the report on the stability of block mattresses under propeller-induced loads, because of the fact that usually in reality the concrete is poured directly onto the geotextile, it was very important to take into consideration the added mass (glue and screws) of the connection of the blocks to the geotextile. For that reason, the added weight of these connections was compensated in the weight of the blocks. In addition, the small thickness that the geotextile has at prototype scale had as a result another added mass, which was also compensated by the weight of the blocks (since the thickness of the geotextile at model could not be smaller than the prototype).

Furthermore, the stiffness of the joints, which in reality is achieved mainly by pouring the concrete onto the geotextile, was simulated by using both glue and screws. This resulted in a stiff connection. Consequently, the effect of this difference (between directly pouring concrete on the geotextile and use of glue-screws) is expected to be limited.

Another aspect, which is considered to be extremely interesting, is the stiffness of the geotextile. In reality, the geotextile of a block mattress is considered to be very flexible. However, due to the fact that a similar geotextile is used for a smaller block mat, this geotextile is considered to be stiff. Hence, the overturning of the mat can be 'prevented' because of the resistance (increased stiffness) of the geotextile against bending. For that reason, the most flexible geotextile of the market was selected and used. The contribution of the most flexible geotextile to the resistance against overturning is 7% at model, whereas at prototype is around 0.03% (Van Velzen, G., De Jong, M.P.C., 2015).Therefore, the geotextile is a bit stiff at model compared to the prototype.

As far as the permeability of the mattress is concerned, it was selected to be a bit small in order to 'give' more conservative results. Hence, the block mattress is lifted more easily. In that way, by choosing a more conservative solution for the permeability of the mattress, the 'problem' due to the increased stiffness of the geotextile is somehow compensated.

Taking into account all the aforementioned properties of the block mat, it is possible to distinguish between the 'cases' that refer to reality and the 'cases' that should not be taken so much into account (because they are in some way or completely wrong). Firstly, regarding the input of the turbulence, which is analysed further in the next Chapter, it is obvious that placing random stones in order to create a rough layer or even placing hands in the water do not represent a real -life situation. On the other hand, the fact that the eddies (above the block mat) have a length comparable to the block's length, which can be seen in the videos, can be regarded as a representation of reality. Moreover, the incipient motion of the block mat (start of overturning or lifting) is not considered to be affected by scale effects. However, the tensile strength of the geotextile is very large at model and this does not allow the tearing of the geotextile at model (Van Velzen, G., De Jong, M.P.C., 2015). In reality, though, the tearing of the geotextile is a failure mode, but it is not examined in this Master Thesis project.

4. Experiment (test series)

The next step after the preparation and the first thoughts, which were considered in order to organise the basic points (that are described in the previous chapter) of these tests, was to set up the experiment in the Water Lab of TU Delft. In particular, the experiment on the stability of block mats (betomat GS-VB-15) under flow conditions that was held in the Water Lab of TU Delft can be divided in three test series, which are described thoroughly in this chapter. Since the physical testing (and modeling) on block mats is in the early stages yet, all of these test series target firstly the better understanding and interpretation of the reasons that cause the failure of block mats.

4.1 First test series

The first test series of the experiment focus on the stability of a block mat with both edges open and free to move (Figure 4.1). Specifically, these test series were done in order to examine if it is possible for a block mat to withstand turbulent flow and turbulent conditions without having an upstream 'fixed' point that enhances its stability.

Figure 4.1 Test on a 'free' to move block mat

Regarding the first test series two cases were examined:

- In the first case rough rocks and large concrete blocks were placed randomly upstream of the block mat (Figure 4.1) that was tested and the discharge was gradually increased till the moment that failure occurred

- In the second case the free to move block mat is firstly subjected to a flow without turbulence and suddenly turbulence is created by simply putting hands in the water in front of the block mat

The results (Chapter 5) of both of these two cases (first test series) are qualitative, since videos were recorded and pictures displaying the frame to frame failure were taken.

4.2 Second test series

In the second test series the stability of a block mat with a 'fixed' first edge and an open-end edge (Figure 4.2) was examined. Particularly, in these test series a 'fixed' edge was created for the first row of blocks of the mat by simply placing the geotextile of the edge beneath the artificial bed (which has small stones glued on it) of the flume (Figure 4.3). The main objective of these series was to measure the velocities and the turbulence intensities that lead to instability of the open-end edge or middle of the mat (up and down movement) and observe the conditions that could possibly have as result the turning over of the free edge. For these reasons, the second test series were divided in two parts:

- Measuring the velocity and turbulence at open-end edge (or in the middle of the mat if there is failure) at failure and before failure
- Observe the effect of the 'fixed' edge on the stability of the block mat

The magnitude of movement (of the block mat) before failure was considered to be up to 0.5 cm and at failure around 1 cm to 1.5 cm (which is slightly more than the half height of a block).

Figure 4.2 The open-end edge of the block mat

Figure 4.3 'Fixed' edge by placing the geotextile of the mat under the artificial bed

The velocity and the characteristics of turbulence were measured using an Electromagnetic Flow meter (EMS) which is shown in Figure 4.4 with a sampling frequency of 100 Hz. Practically, the EMS was measuring volts which were translated in m/sec, giving the corresponding 'instantaneous' flow velocity.

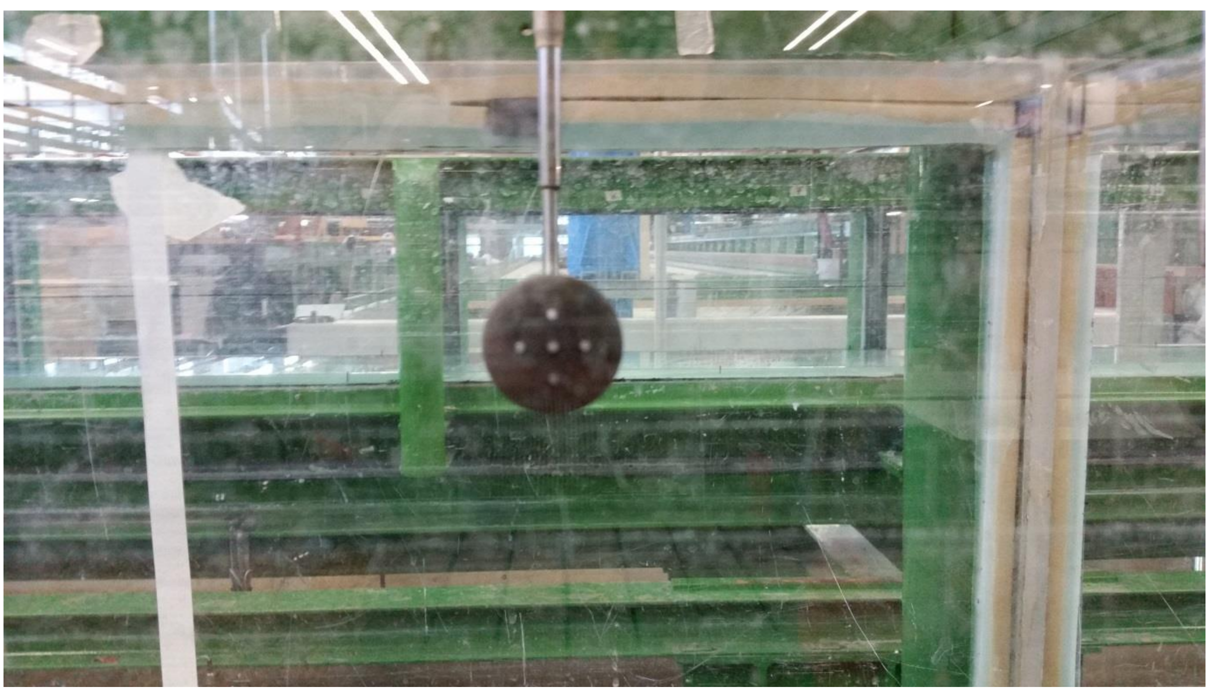

Figure 4.4 Electromagnetic Flow meter (EMS)

As far as the experiment (second test series) is concerned the first step was to create 'appropriate' conditions for the block mattress to fail. This step was considered to be the most difficult part of the whole test series. The fact that an upstream 'fixed' edge was selected led to a very stable solution for the block mat. For that reason the large concrete blocks that were placed upstream of the free-to-move block mat in the first test series, were placed (in a random set-up) in different cross sections and in most cases above the block mat (Figure 4.5) during the second test series.

Figure 4.5 Placement of concrete blocks in different locations above (and outside) the block mat

Regarding the measurements that were done, the EMS was placed around 2 cm above the block mat in the location where the maximum magnitude of movement was noticed (either edge or middle). Since the water level downstream was between 7 cm and 10 cm and the fact that the EMS had a diameter of around 3 cm, it was not possible to put the EMS in different water levels. Therefore, the height, at which the EMS was placed, was limited by the water level downstream of the large concrete blocks. However, in all cases an almost same height was tried to be achieved in order for the results to be comparable. The measurements that were done refer to velocities in x and z directions every 0.01 sec (each measurement lasted around 2 minutes).

Apart from the measurements, videos were also recorded for the interpretation and the better understanding of the physical processes that lead to the instability of block mattresses.

4.3 Third test series

Finally, the third test series were only done in order to observe the behaviour of the transition between two consecutive placed block mats. In particular, during these series the effect of having or not a gap between two consecutive block mattresses was tested, in order to understand how failure occurs in this case (transition).

The two cases that were examined are:

- A transition in which there is a gap between the two block mats (the geotextile of the second mat is placed beneath the geotextile of the first mat)(Figure 4.6)
- A transition in which there is not a gap between the block mats and the geotextile of the second mat is placed beneath the last row of blocks of the first block mat (overlap)(Figure 4.7)

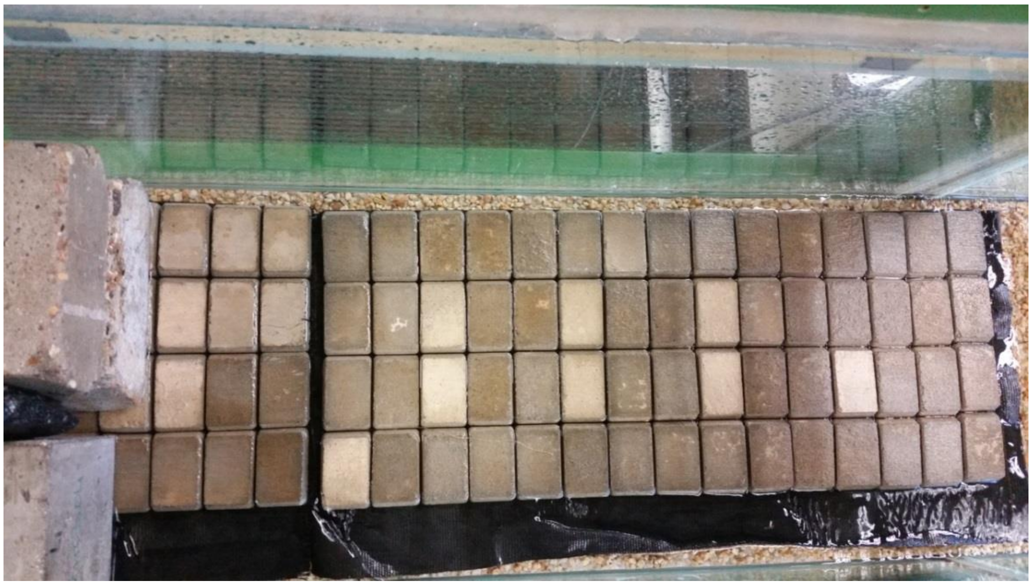

Figure 4.6 Transition with gap between the block mats

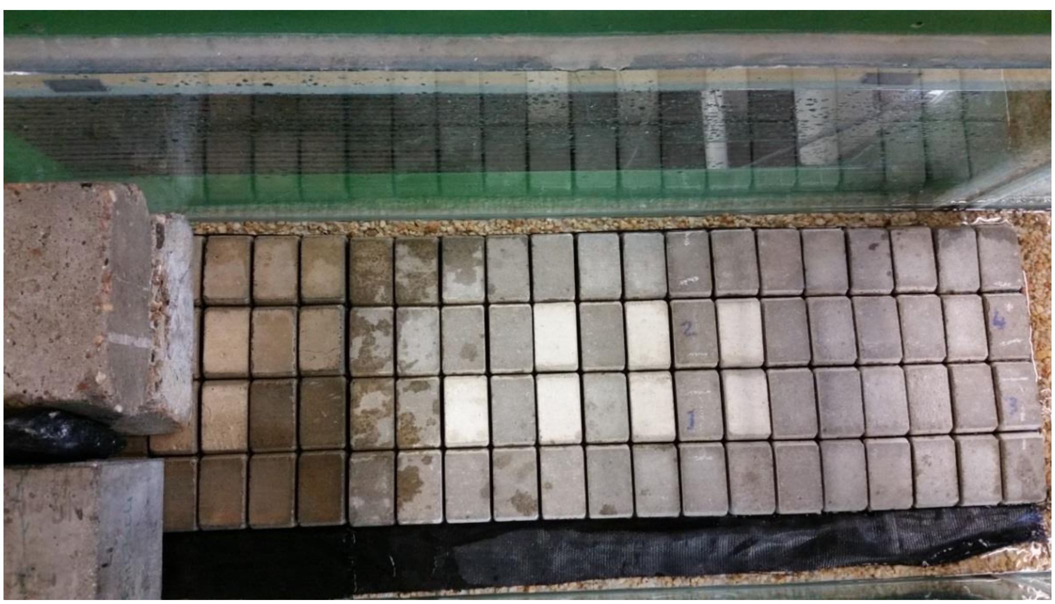

Figure 4.7 Transition without gap (overlap) between the block mats

As it can be observed from both Figures large concrete blocks and rocks were placed upstream of the transition in order to create a turbulent flow. The discharge was also gradually increased in these two cases till the moment of failure. The results of the third test series, which are presented in the next

Chapter, are mainly qualitative and there are also recorded videos and photos before and after the failure of the transition.

5. Results – Analysis – Discussion

In this Chapter the results of the test series, which are described in the previous Chapter, are presented. For each test series there is an analysis about the results and the consequences that they have in future experiments and practical applications of block mattresses.

5.1 First test series

As it is mentioned previously, the first test series refer to the consequences of having a block mat, with both edges free to move, subjected to turbulent flow. Specifically, during these test series two different cases were examined. In the first case some rough rocks and big concrete blocks were placed upstream of the block mat in order to create a turbulent flow, whereas in the second case the turbulent flow was created by simply putting hands in the water. In Figure 5.1 the failure of the block mat (first case) is depicted frame to frame.

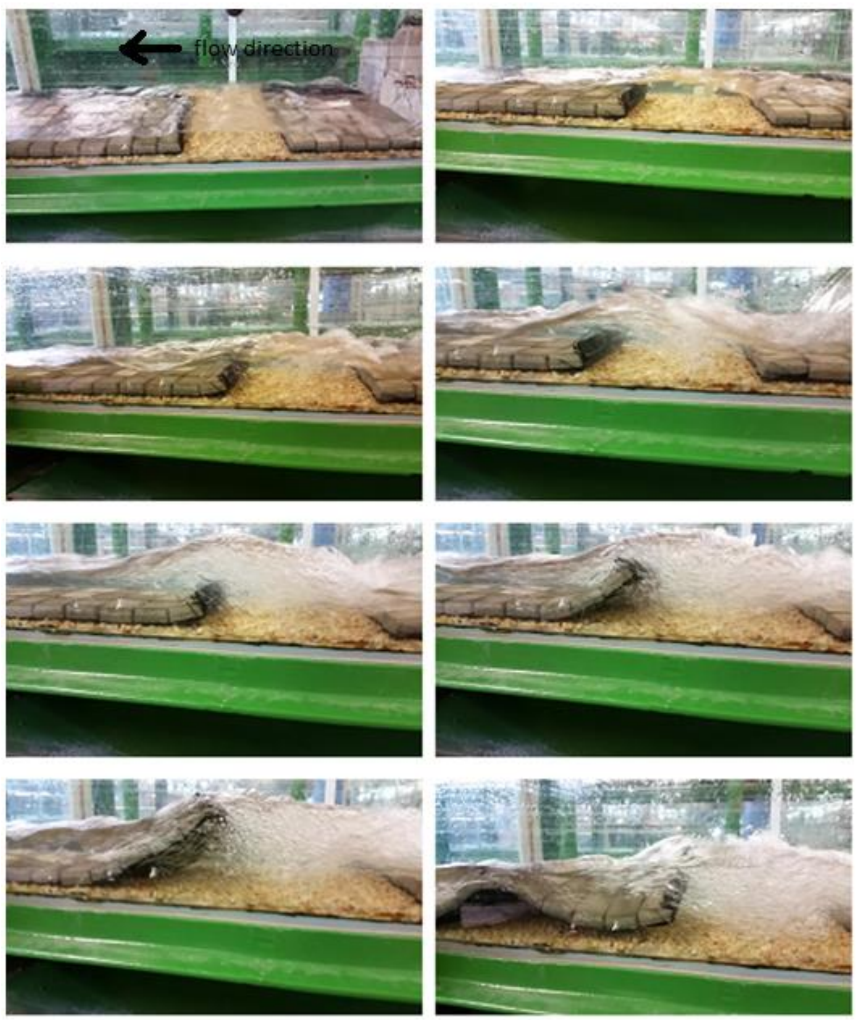

Figure 5.1 Frame to frame failure of the block mat (rocks and blocks upstream)

In Figure 5.2 the frame to frame failure of the block mat is shown for the second case (hands in the water).

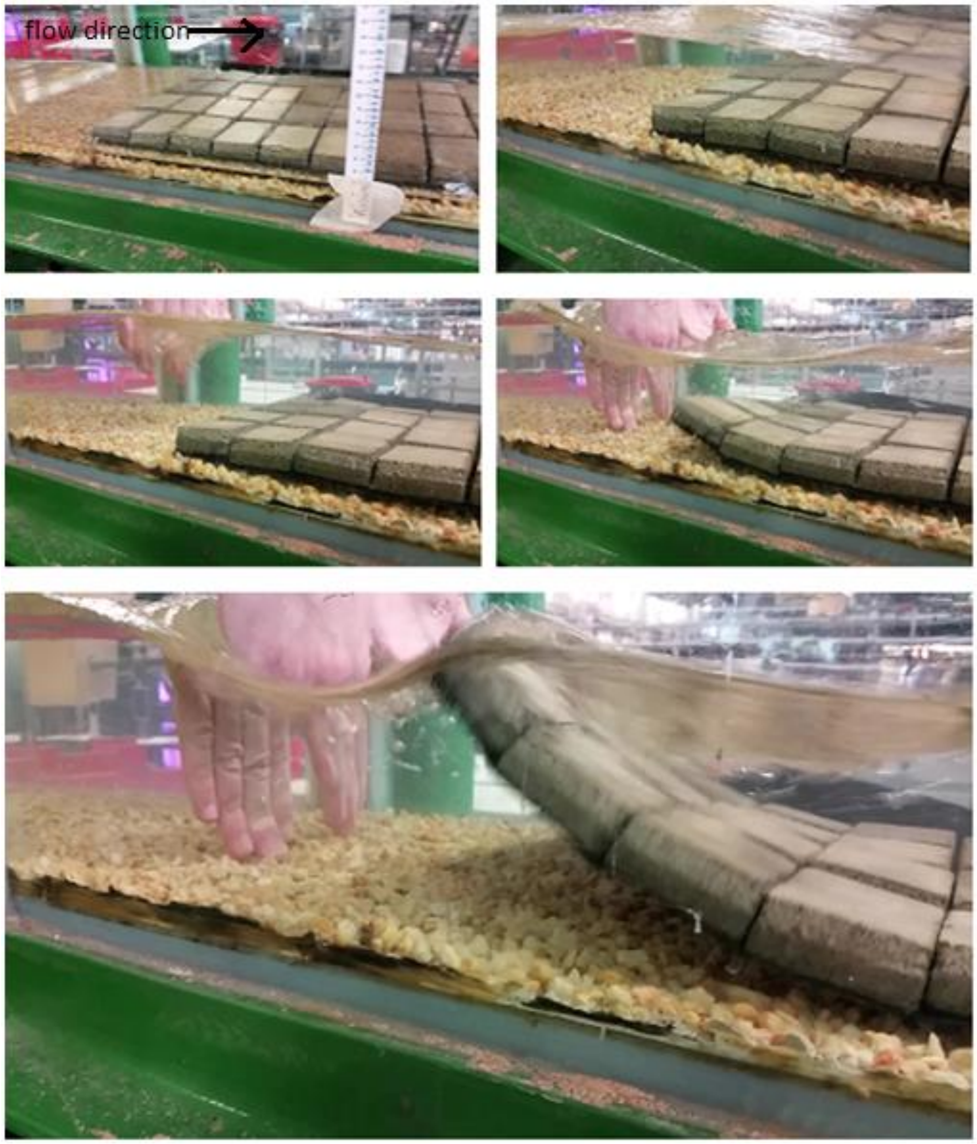

Figure 5.2 Frame to frame failure of the block mat (hands upstream)

As it can be observed from both Figures, the failure of the block mat in these two cases is identical. Initially, the first row of blocks starts to moves upward, then the flow 'manages' to pass under the mat and eventually the whole block mat is taken away towards the flow direction. The only difference between these two cases is that in the first case the water flow was increased gradually till the point that a huge instability of the block mat occurred (failure), whereas in the second case the hands were put in the water abruptly causing the immediate 'response' (failure) of the block mat. The conclusion, though, that can be derived by the first test series is that it is extremely important to somehow have a 'fixed' first edge (upstream) in order not for the block mat to be taken away, which is possible to happen if the upstream edge is totally unprotected.

5.2 Second test series

Analysing the conclusions of the first test series, it was obvious that a 'fixed' upstream edge was needed. The upstream edge is very sensitive to turbulent conditions, because flow can easily pass under the block mat leading to the overturning of the edge. For that reason, a 'fixed' first edge of the block mat was chosen, as it is shown in Figure 5.3 (by placing the geotextile of the edge under the artificial bed).

Figure 5.3 'Fixed' upstream edge of the block mat

The second (downstream) edge of the block mat was free to move. Main objective of these test series was to measure the flow conditions (velocity and turbulence) that lead to the failure of the open-end edge of the block mat (or the failure of middle blocks of the block mat). In order to create the appropriate conditions at the area of interest (edge and middle blocks), rough rocks and large concrete blocks were placed above (and outside) the block mat in different cross sections. By the elaboration of these measurements, graphs like the one shown in Figure 5.4 were exported, that present the flow velocity signal (usually in two cases: a)before failure and b)at failure). In that way, by analysing the velocity characteristics the mean value of the velocities both in x and z direction could be calculated. In addition, the hydrodynamic measurements were chosen to be performed with a frequency of 100 Hz, in order to be able to obtain turbulent properties from the flow velocity signals. Specifically, besides the mean velocity, the standard deviation can also be calculated, which refers to the square root of the averaged squares of the fluctuations. By dividing the standard deviation with the mean value of the flow velocity, the turbulence intensity can be derived, as it can be observed in the following two equations.

$$r_x = \frac{\sqrt{\overline{\acute{u}^2}}}{\bar{u}} \tag{5.1}$$

$$r_z = \frac{\sqrt{\overline{\acute{w}^2}}}{\bar{u}} \tag{5.2}$$

Where:

$\acute{u}$, $\acute{w}$ refer to the fluctuations of Vx and Vz respectively

$\bar{u}$ is the mean velocity in x direction (Vx)

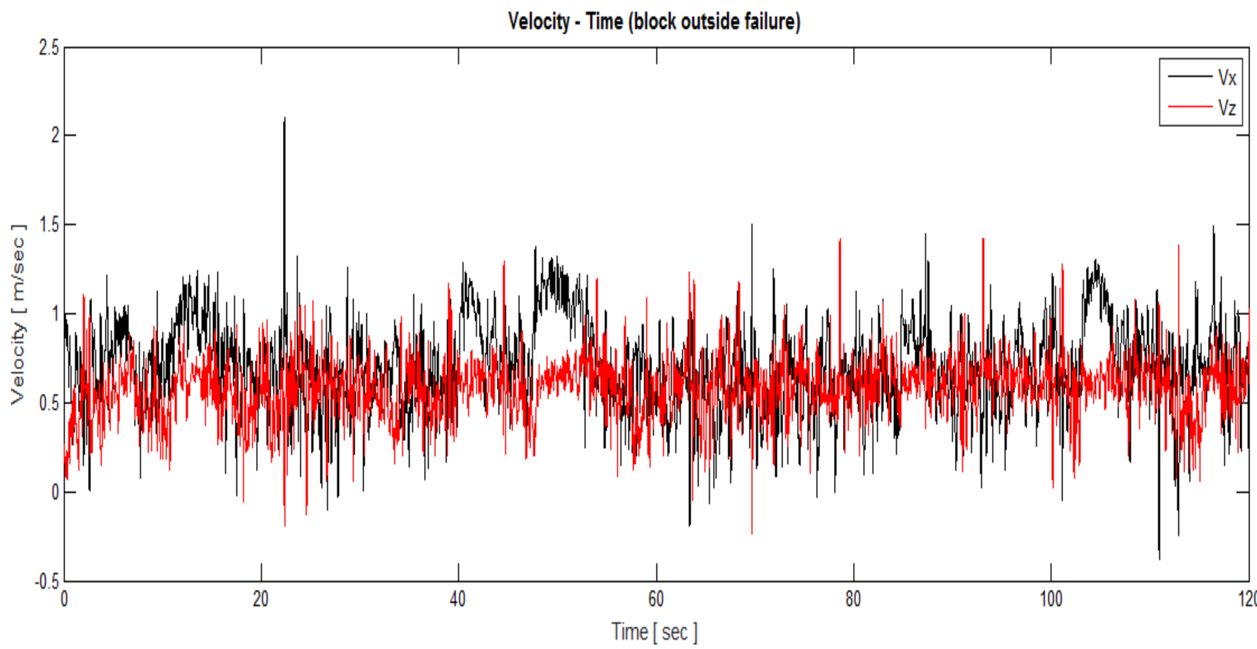

Figure 5.4 Velocity – Time (block outside failure)

It is worth mentioning that the 'block outside failure' which is in the parenthesis of the title refers to the configuration-set up of the experiment. In the following Figure, the regions (of Figure 5.4) that present an extreme importance are displayed (zoom in). Specifically, it is obvious that the fluctuations around mean velocity are not constant in value or with time. As it can be observed in Figure 5.5, there can be fluctuations of the velocity with duration between 2 and 5 seconds (pointed with an arrow in these two regions), in which the instant velocity is even doubled. These fluctuations are considered to be far more important compared to fluctuations that last less than 1 second.

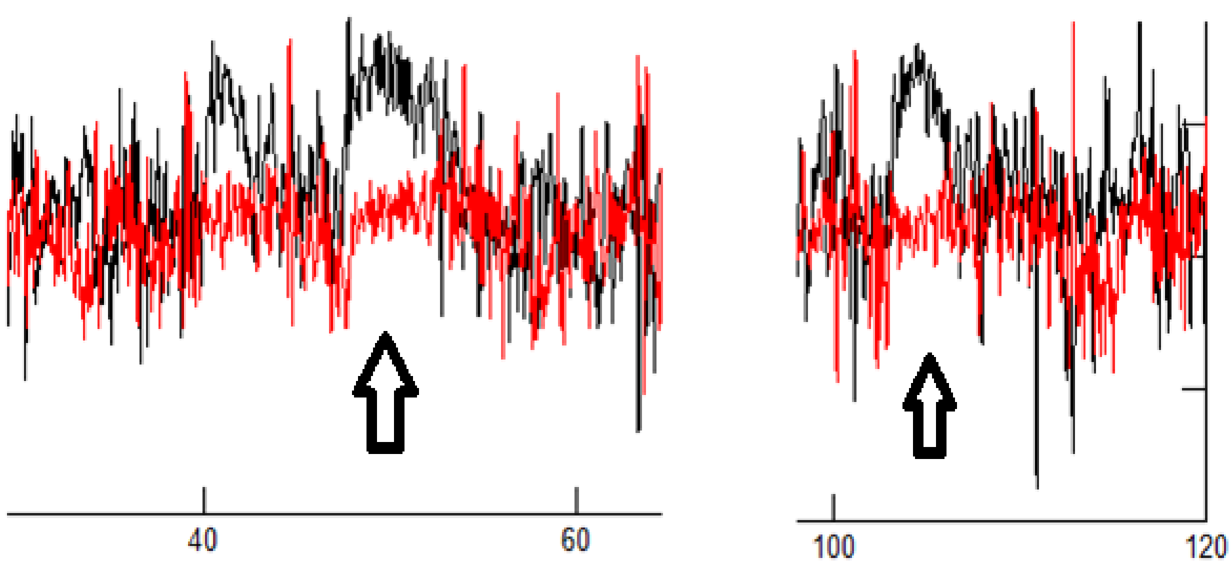

Figure 5.5 Zoom in interesting regions (Velocity-time)

The frame to frame failure of one of the tested open-end edges is shown in Figure 5.6. It is worth mentioning that there was a frequent up and down movement of the edge blocks of the mat.

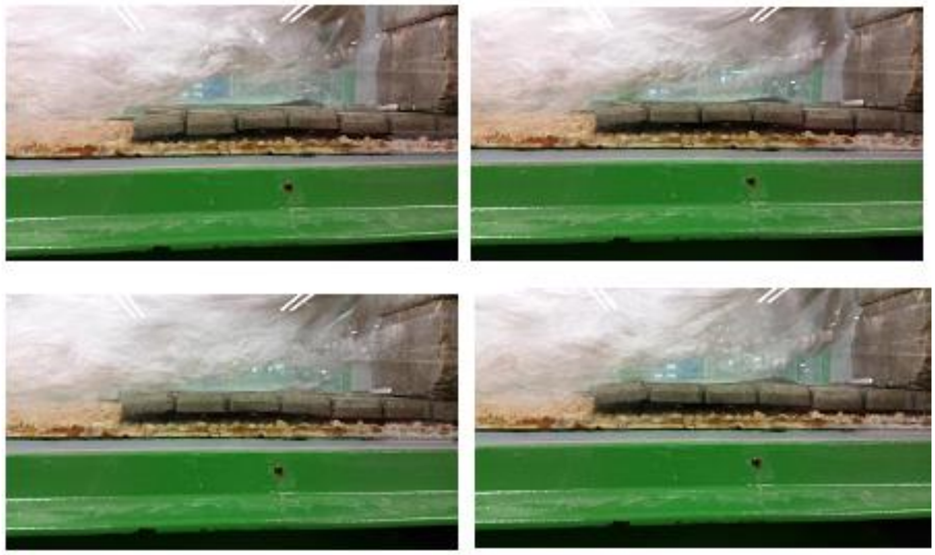

Figure 5.6 Frame to frame failure of open-end edge

Another interesting aspect, that has to do with qualitative analysis and the 'tendencies' of the measured velocities in the free-to-move edge, showed that the edge of the block mat was unstable for smaller values of velocity in combination with higher values of turbulence (instead of high velocities with normal turbulence). This implies that the level of turbulence is considered to be more important compared to the value of mean velocity. This is a quite interesting conclusion since the Pilarczyk's formula concerns more about the mean value of the velocity close to the block mat, which seems to be irrelevant according to the measurements of this experiment. Actually, Pilarczyk's formula takes into account turbulence but as a constant value according to the hydraulic structures or propeller jets or morphological aspects (outer bends) of the channel that influence the stability of the block mat. Although, according to the second test series of this experiment turbulence seems to be extremely important and it is not sufficient to be regarded as a constant value. In the following table, the values of mean velocity (in x and z direction) and turbulence intensity are presented for two different locations of concrete blocks above the block mat (before and after the failure).

Configuration	*Before failure*	*At failure*
Concrete blocks above the block mat are placed in such a way that **five** blocks of the block mat are open from the edge	V_x= 0.9204 m/sec	V_x= 0.7910 m/sec
	r_x= 0.329	r_x= 0.383
	V_z=0.6464 m/sec	V_z= 0.6456 m/sec
	r_z= 0.253	r_z= 0.331
Concrete blocks above the block mat are placed in such a way that **four** blocks of the block mat are open from the edge	V_x=0.8825 m/sec	V_x=0.5876 m/sec
	r_x= 0.185	r_x= 0.508
	V_z= 0.6807 m/sec	V_z= 0.6918 m/sec
	r_z= 0.179	r_z= 0.348

Table 5.1 Velocities and turbulence intensities right before failure and at failure

As it can be observed by the measurements in Table 5.1, the crucial factor that leads to failure is the level of turbulence, since high levels of it even with lower values of velocity can cause instability to the block mat.

In addition, the elaboration of the measurements that were done for failure of last row blocks and failure of middle blocks converge to the conclusion that the combination of mean velocity and turbulence is important. This can be noticed in Figures 5.7 and 5.8, in which a linear regression for combinations of mean velocity and turbulence intensity during failure has been applied.

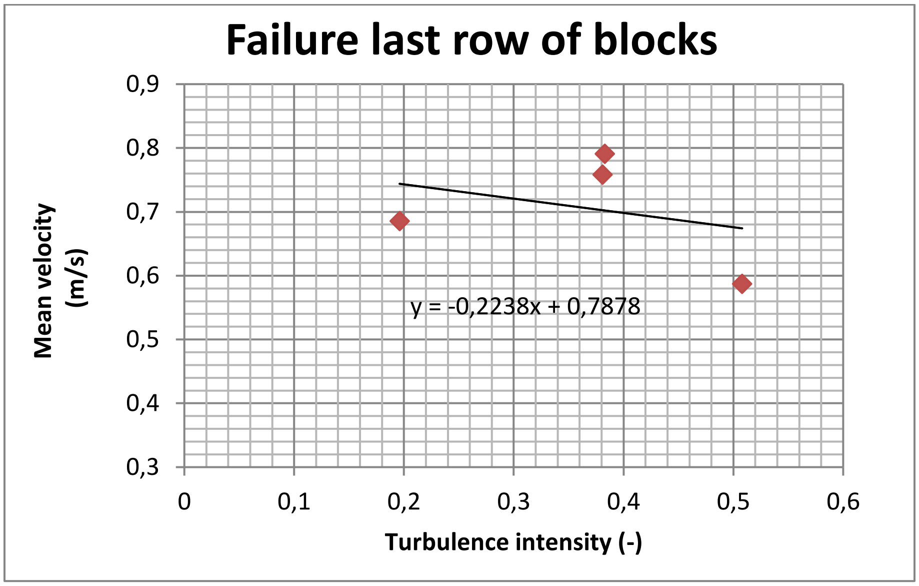

Figure 5.7 Velocity – Turbulence intensity (failure open-edge blocks)

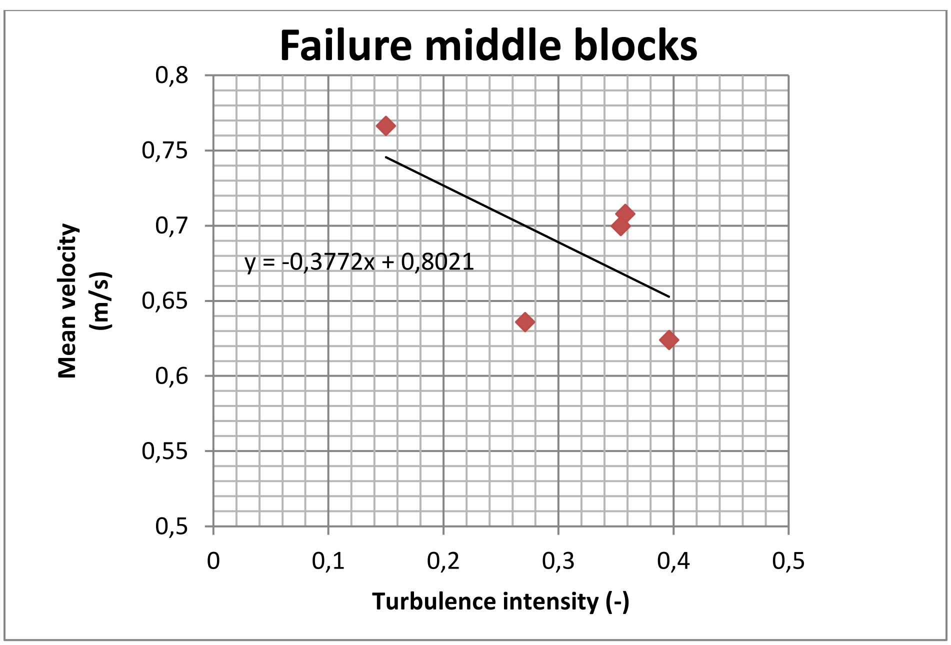

Figure 5.8 Velocity – Turbulence intensity (failure middle blocks)

As it can be observed from both Figures (5.7, 5.8), it is possible for the block mat to fail, even with low values of mean velocity, if the levels of turbulence intensity are high. This is another proof for the importance-role of turbulence on the stability of block mats. The lines in both diagrams are indicative for the combinations of mean velocity and turbulence intensity that lead to failure. However, the linear regression which is applied in both diagrams seems to be not so representative especially for the data of Figure 5.7. In that case the available data from the measurements are not enough to lead to a safe result, but examining these diagrams qualitatively and analysing their trends, the above mentioned conclusion for the major role of turbulence is supported.

In addition, in the two following Figures (5.9, 5.10) the scattered data for combinations of mean velocity and turbulence intensity for stable and unstable conditions of open edge blocks and middle blocks are presented.

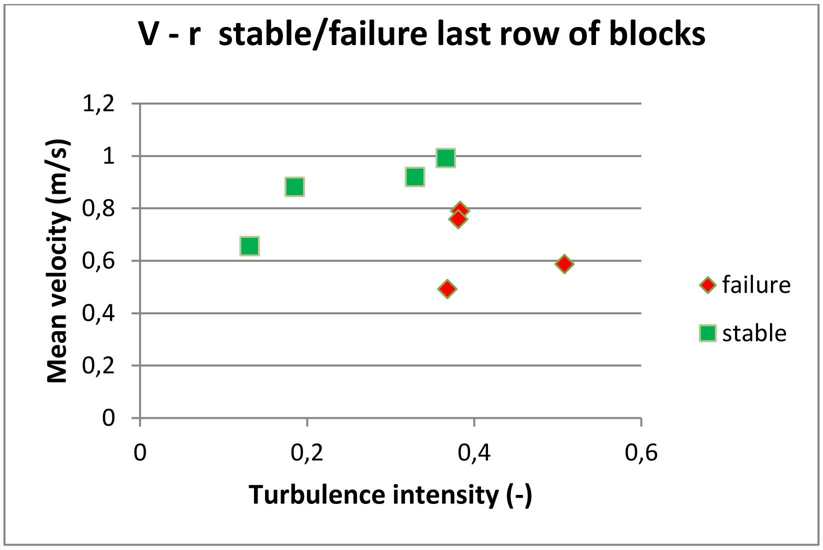

Figure 5.9 Stable/unstable points for open edge blocks

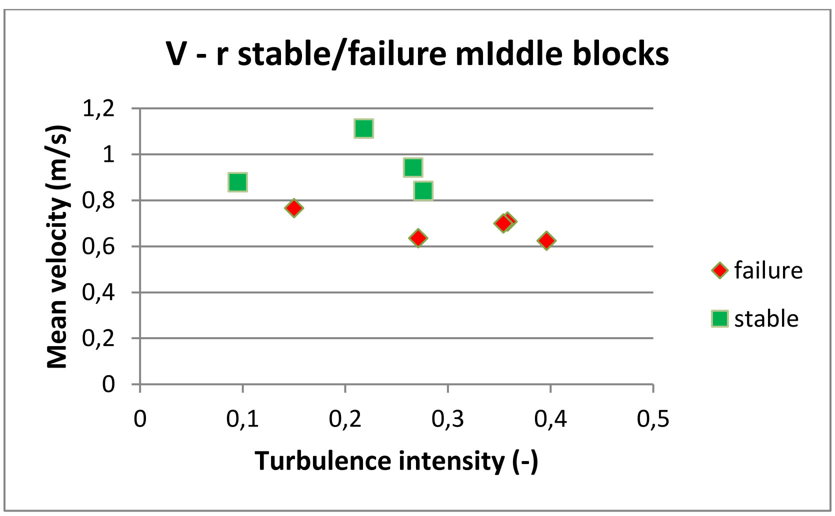

Figure 5.10 Stable/unstable points for middle blocks

It is obvious in both Figures that higher levels of turbulence seem to be more critical compared to higher velocities. Moreover, a dashed line is drawn (Figures 5.11 and 5.12) in order to separate the stable points and the unstable points. It is worth mentioning that in the case of edge blocks the stable 'region' seems to be in the upper left part of the diagram, whereas the unstable 'region' is located in the lower right part. According to this case, turbulence plays the most important role, since high levels of it may lead to potential failure of block mats. In the case of middle blocks a similar pattern is observed, if the pointed with the arrow measurement is excluded. This measurement seems not to be accurate and deviates a lot from the bulk of the other failure points (measurements).

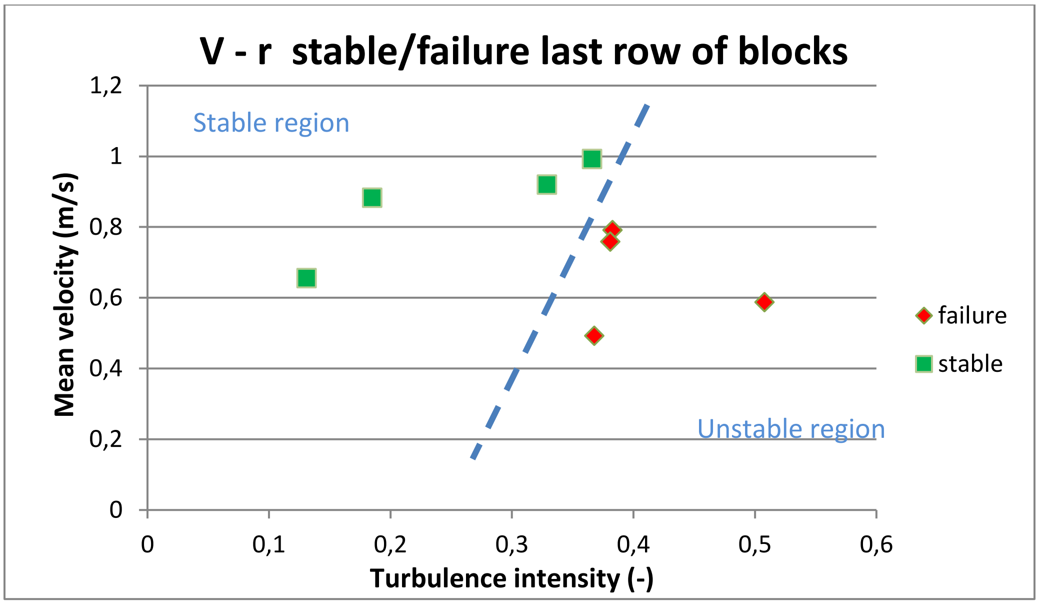

Figure 5.11 Separating stable/unstable 'regions' for open edge blocks

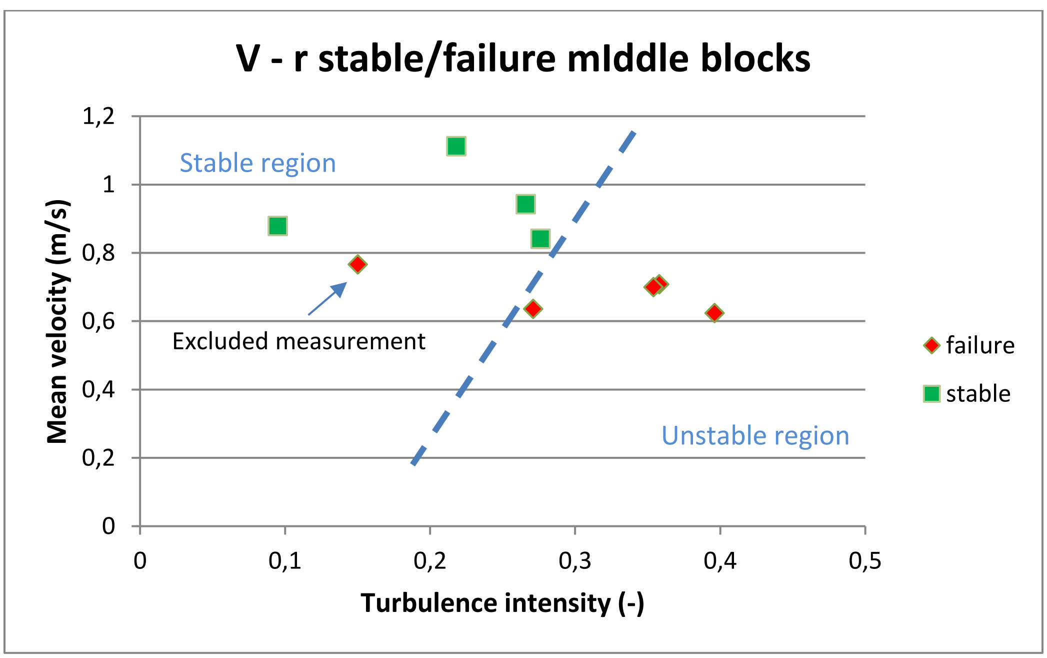

Figure 5.12 Separating stable/unstable 'regions' for middle blocks

Furthermore, it is extremely interesting to compare the experimental measurements (velocity, turbulence intensity) with the application of Pilarczyk's equation for the stability of block mats. This comparison is done for two different cases. In the first case, the velocity, which was measured during the experiments, is used as a known (same) variable in the Pilarczyk's formula in order to determine the turbulence intensity. Hence, there is a comparison between the 'experimental' turbulence intensity and the 'Pilarczyk's' turbulence intensity. In the second case, the turbulence intensity, which was measured during the experiment, is the known (same) variable and the velocity is calculated by Pilarczyk's equation. Therefore, there is a comparison between the 'experimental' velocity and the 'Pilarczyk's' velocity.

The Pilarczyk's equation which was analysed further in Chapter 2 is presented again in Equation 5.3.

$$\frac{U^2/2g}{\Delta * D} = \frac{\psi_{cr}}{\varphi_{sc} * 0.035} \frac{k_{sl} * k_t^{-2} * k_h^{-1}}{1} \tag{5.3}$$

The values (assumptions) that were used for the parameters according to Table 2.2 are:

ψ_{cr}=0.070 for block mats

ϕ_{sc}=0.5 for middle block of the mat - ϕ_{sc}=1 for edge (last blocks) of the mat

Δ=1.31 relative density

g=10 m/s^2

k_h=1 measuring very close to the mat

k_{sl}=1 horizontal bed

D=0.019 m block thickness

In order to relate the parameter k_t^2 (which refers to turbulence) with the turbulence intensity, there is an equation (5.4) according to the Rock Manual 2007.

$$k_t = \frac{1 + 3r}{1.3} \tag{5.4}$$

The results of the first case, in which velocity is known from the experimental measurements and turbulence intensity is calculated using Pilarczyk's formula are presented in Table 5.2 and Table 5.3 for edge blocks and middle blocks respectively.

Pilarczyk's approach	Test 05	Test 06	Test 16	Test 18
	V_x=0.7910 m/s	V_x=0.7584 m/s	V_x=0.5876 m/s	V_x=0.6855 m/s
	r=0.21	r=0.24	r=0.40	r=0.30
Experimental measurements	Test 05	Test 06	Test 16	Test 18
	V_x=0.7910 m/s	V_x=0.7584 m/s	V_x=0.5876 m/s	V_x=0.6855 m/s
	r=0.383	r=0.381	r=0.508	r=0.196

Table 5.2 Comparison between Pilarczyk and experiment for same velocity (last blocks at failure)

The next Figure (5.13) refers to Table 5.2 and shows the results of the comparison between experimental measurements and Pilarczyk's approach for edge blocks of the mat.

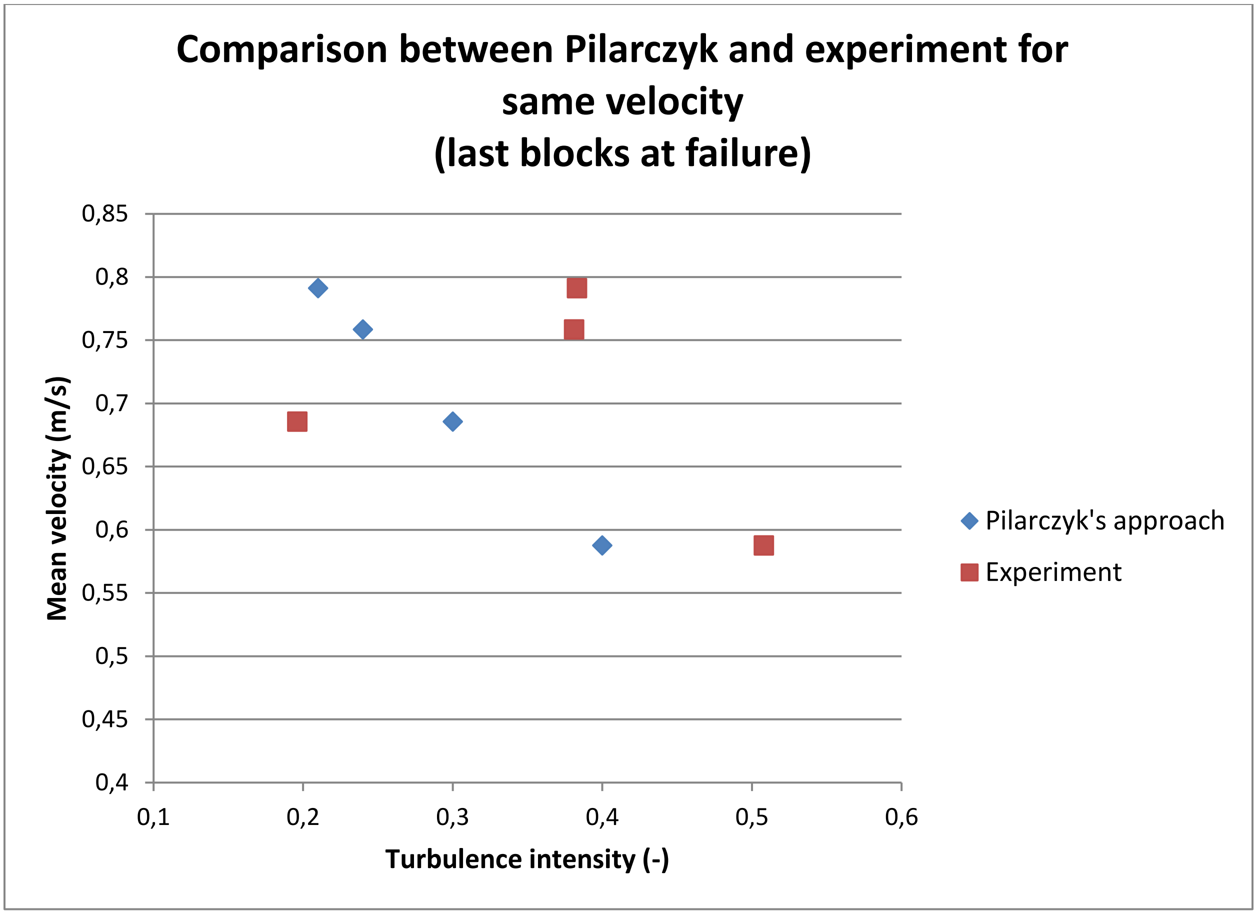

Figure 5.13 Comparison between Pilarczyk and experiment for same velocity (last blocks at failure)

As it can be observed from Figure 5.13, in most of the cases Pilarczyk's equation seems to underestimate the 'strength' of block mats (at the edge), since for the same value of velocity Pilarczyk's formula considers that failure occurs for lower values of turbulence intensity compared to the experimental measurements of turbulence intensity at failure.

Pilarczyk's approach	Test 08	Test 11	Test 12	Test 14	Test 21
	V_x=0.7664m/s	V_x=0.6359m/s	V_x=0.6239m/s	V_x=0.7078m/s	V_x=0.6997m/s
	r=0.46	r=0.63	r=0.65	r=0.53	r=0.54
Experimental measurements	Test 08	Test 11	Test 12	Test 14	Test 21
	V_x=0.7664m/s	V_x=0.6359m/s	V_x=0.6239m/s	V_x=0.7078m/s	V_x=0.6997m/s
	r=0.15	r=0.271	r=0.396	r=0.358	r=0.354

Table 5.3 Comparison between Pilarczyk and experiment for same velocity (middle blocks at failure)

The next Figure (5.14) refers to Table 5.3 and shows the results of the comparison between experimental measurements and Pilarczyk's approach for middle blocks of the mat.

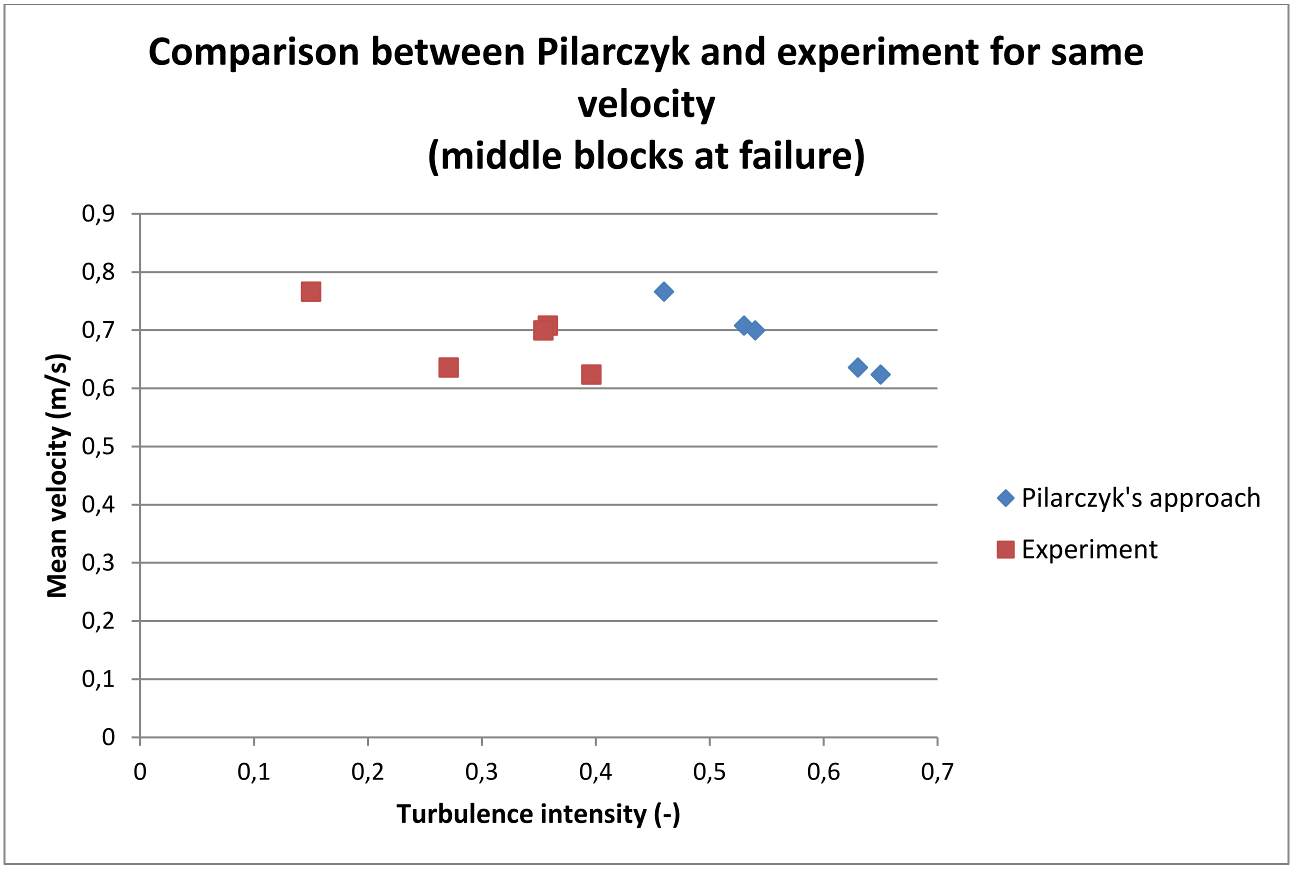

Figure 5.14 Comparison between Pilarczyk and experiment for same velocity (middle blocks at failure)

For middle blocks Pilarczyk's equation seems to have the opposite result compared to edge blocks. Specifically, as it can be observed from Figure 5.14 Pilarczyk's formula overestimates the 'strength' of the block mat (middle blocks), since for the same velocity Pilarczyk's equation considers failure to occur for higher values of turbulence intensity compared to the experimental measurements.

The results of the second case, in which turbulence intensity is known from the experimental measurements and velocity is calculated using Pilarczyk's formula are presented in Table 5.4 and Table 5.5 for edge blocks and middle blocks respectively.

Pilarczyk's approach	Test 05	Test 06	Test 16	Test 18
	V_x=0.6036 m/s	V_x=0.6053 m/s	V_x=0.5139 m/s	V_x=0.8168 m/s
	r=0.383	r=0.381	r=0.508	r=0.196
Experimental measurements	Test 05	Test 06	Test 16	Test 18
	V_x=0.7910 m/s	V_x=0.7584 m/s	V_x=0.5876 m/s	V_x=0.6855 m/s
	r=0.383	r=0.381	r=0.508	r=0.196

Table 5.4 Comparison between Pilarczyk and experiment for same turbulence intensity (last blocks at failure)

The next Figure (5.15) refers to Table 5.4 and shows the results of the comparison between experimental measurements and Pilarczyk's approach for edge blocks of the mat.

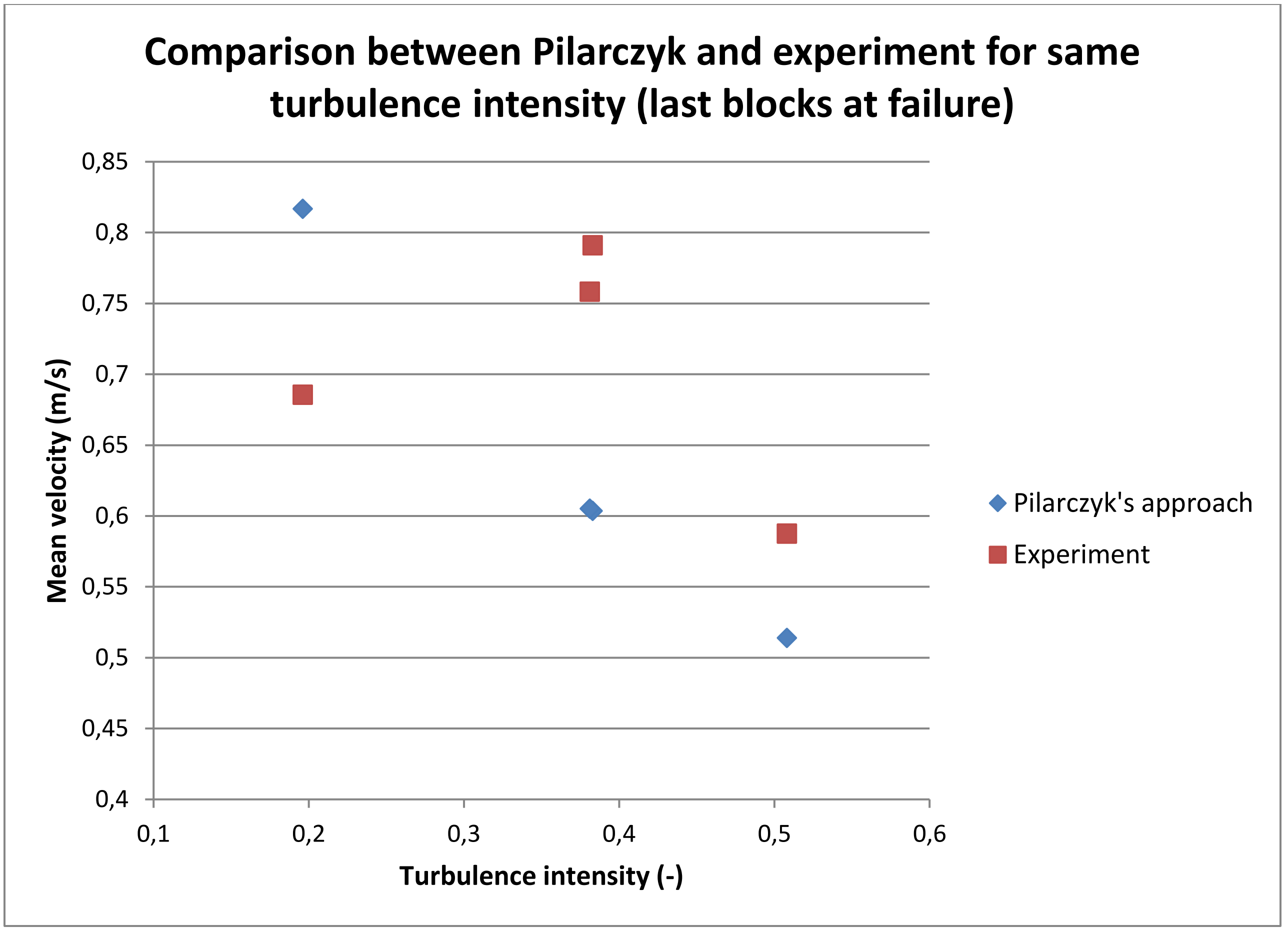

Figure 5.15 Comparison between Pilarczyk and experiment for same turbulence intensity (last blocks at failure)

As it can be observed from Figure 5.15, in most of the cases Pilarczyk's equation seems to underestimate the 'strength' of block mats (at the edge), since for the same value of turbulence intensity Pilarczyk's formula considers that failure occurs for lower values of velocity compared to the experimental measurements.

Pilarczyk's approach	Test 08	Test 11	Test 12	Test 14	Test 21
	V_x=1.2651m/s	V_x=1.0118m/s	V_x=0.8384m/s	V_x=0.8845m/s	V_x=0.8896m/s
	r=0.15	r=0.271	r=0.396	r=0.358	r=0.354
Experimental measurements	Test 08	Test 11	Test 12	Test 14	Test 21
	V_x=0.7664m/s	V_x=0.6359m/s	V_x=0.6239m/s	V_x=0.7078m/s	V_x=0.6997m/s
	r=0.15	r=0.271	r=0.396	r=0.358	r=0.354

Table 5.5 Comparison between Pilarczyk and experiment for same turbulence intensity (middle blocks at failure)

The next Figure (5.16) refers to Table 5.5 and shows the results of the comparison between experimental measurements and Pilarczyk's approach for middle blocks of the mat. It is interesting to notice that again Pilarczyk's formula overestimates the 'strength' of block mats (middle blocks), since for the same levels of turbulence Pilarczyk's equation considers that failure occurs for higher velocities compared to the experimental measurements.

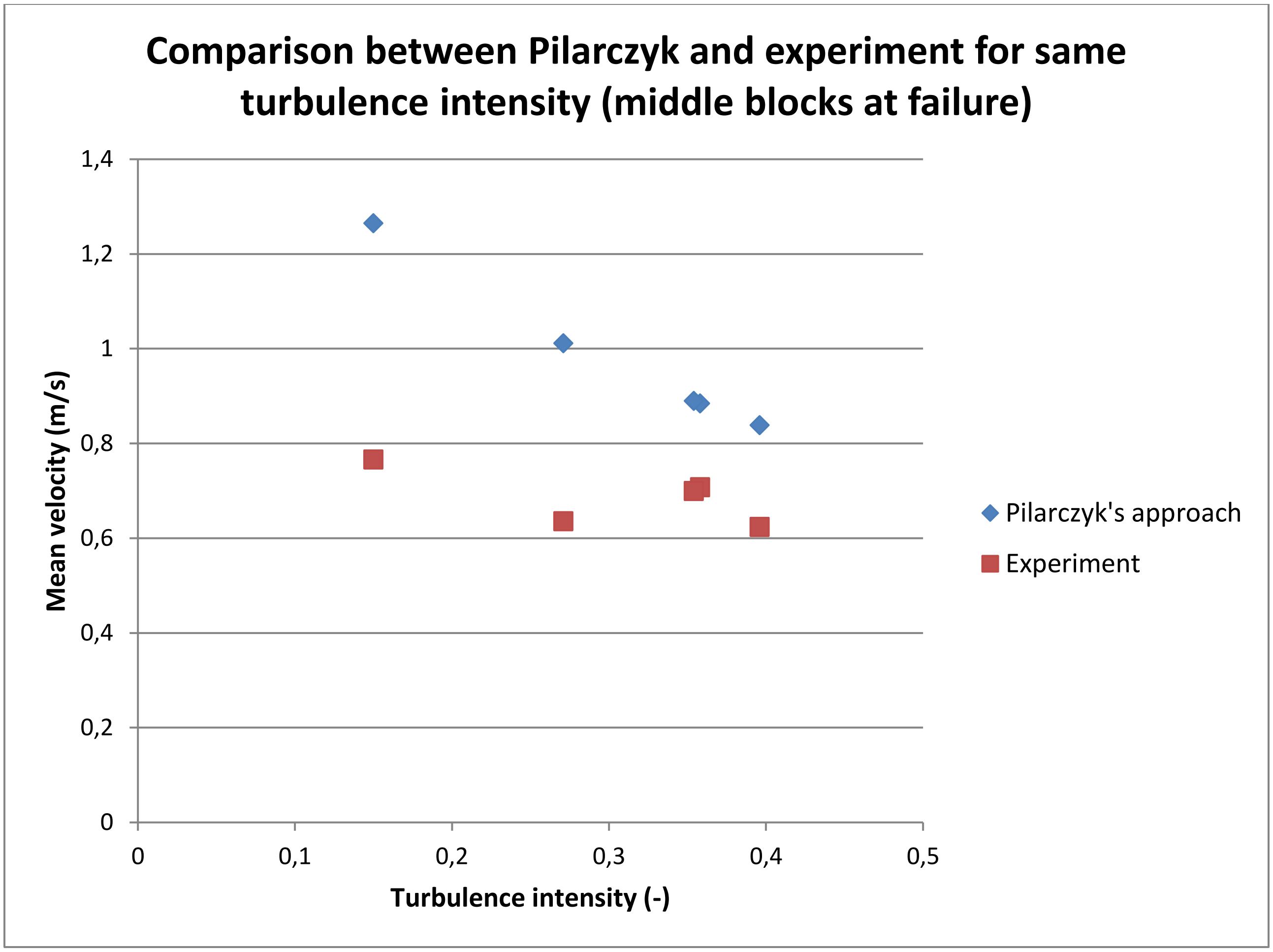

Figure 5.16 Comparison between Pilarczyk and experiment for same turbulence intensity (middle blocks at failure)

Consequently, according to the previous Figures that display the differences between the Pilarczyk's approach and the experimental measurements, it is obvious that Pilarczyk's formula tends to underestimate the 'strength' of the block mats considering the edge blocks (last blocks), whereas it seems to overestimate the 'strength' of the block mattresses considering the middle blocks (continuous layer). The main reason for this difference in Pilarczyk's approach between edge blocks and middle blocks has to do with the assumption for the value of the stability factor ϕ_{sc}. In particular, the suggested value for ϕ_{sc} for open edges (last row of blocks) of block mattresses according to Pilarczyk is ϕ_{sc}=1, whereas for middle blocks (continuous protection from block mats) is ϕ_{sc}=0.5. The different values of the stability factor are strongly affected by the integrity of the system. Specifically, exposed and open edges need a higher value of the stability factor, which is recommended as a safe value, whereas lower values refer to systems with higher integrity. For these reasons, selecting a stability factor ϕ_{sc}=1 for edge blocks led to an underestimation of their 'strength', whereas selecting a stability factor ϕ_{sc}=0.5 for middle blocks had as a result the overestimation of the mat's 'strength'.

Another interesting and important aspect that needs to be taken into account has to do with the fact that when the concrete blocks (responsible for creating the turbulent flow) were placed upstream of the ‘fixed’ edge of the block mat, as presented in Figure 5.17, the blocks of the mat were making a vibrating movement (up and down).

Figure 5.17 Concrete blocks placed upstream of the ‘fixed’ edge

This finding is extremely interesting, because it broadens the region for which the block mats should be checked. Specifically, the connection between the geotextile and the blocks becomes a crucial factor for the stability of the block mats, since the vibration of the mat was observed. In particular, the tear of the geotextile and the breakage of the pins (generally the connection geotextile-blocks) should be considered in the failure modes of a block mat. The frequency of vibrations is also important and it should be compared to the eigenfrequency of the block mat in order to avoid resonant conditions that could lead to failure. All the aforementioned reasons conclude to the fact that the stability of a block mat may also be a fatigue problem, since the vibrations of it are responsible for the gradual degradation of the materials that it consists of. This is another indication that the Pilarczyk’s formula is not sufficient, since it considers the value of mean velocity as the most important factor. On the other hand, it would be a good approach to check the behaviour of a block (connected with a geotextile under it) under vibrations in a vibrator. In that way the fatigue problem could be examined and analysed leading to a new area of research for the stability of block mats.

It is worth mentioning that during the experiments of the second test series two different frequencies of vibrations were noticed. The frequency of vibrations for the blocks (individually) of the mat which was around 2 Hz - 4 Hz during failure and the frequency of vibrations for the whole block mat (edge) which was around 0.5 Hz during failure.

Finally, the measurements (data) of the second test series were also used (evaluated) in order to approach the stability parameters that were presented in Chapter 3. Taking into consideration that the flow is non-uniform, the flow 'load' as described by the stability parameter is:

$$(\bar{u} + a\sqrt{k})^2$$

Where,

$\bar{u}$: mean flow velocity

α : turbulence magnification factor

k : turbulent kinetic energy

$$k = \frac{1}{2}(\overline{\acute{u}^2} + \overline{\acute{v}^2} + \overline{\acute{w}^2}) \tag{5.5}$$

Where,

$\acute{u}$: turbulent fluctuations of u

$\acute{v}$: turbulent fluctuations of v

$\acute{w}$: turbulent fluctuations of w

The value of α, which should be constant, is determined at failure as the solution of the equation:

$$(\overline{u_1} + a\sqrt{k_1})^2 = (\overline{u_2} + a\sqrt{k_2})^2 \tag{5.6}$$

The indices 1, 2 refer to the tests from which $\bar{u}$ and k were measured. It is of major importance to mention that only equivalent tests were compared (equated) which means that form the above mentioned process two different values of α were determined; one for edge-block failure (α≈-2.5) and one for middle-block failure (α≈-3.5).

As it can be observed both values are negative, which is not expected. The turbulence magnification factor should be by definition positive. For that reason, these values could not be used for the derivation of a new stability parameter. The negative values of α may be due to the fact that the measurements were not so precise (EMS was interrupting the flow, thus it is not the most appropriate in this situation). Hence, the trends of these measurements should mainly be taken into account.

In Appendix C, the Matlab script and the tables with the calculated values of α are presented. In addition, the value of $\sqrt{\overline{\acute{v}^2}}$, which was not measured during the experiments since the EMS measures in two different directions, is approximated as:

$$\sqrt{\overline{\acute{v}^2}} = \frac{\sqrt{\overline{\acute{u}^2}}}{1.9} \tag{5.7}$$

5.3 Third test series

Main objective of the third test series was to observe the differences in the failure of a transition point between two consecutive block mats, if:

- There is a gap between the two block mats (the geotextile of the second mat is placed beneath the geotextile of the first mat)
- There is not a gap between the block mats and the geotextile of the second mat is placed beneath the last row of blocks of the first block mat (overlap)

In the case that there is a gap between the block mats, the frame to frame failure is shown in Figure 5.18, in which it is obvious that the ‘connection’ between the block mats is totally lost and the second block mattress is taken away with a notable buckling phenomenon on it.

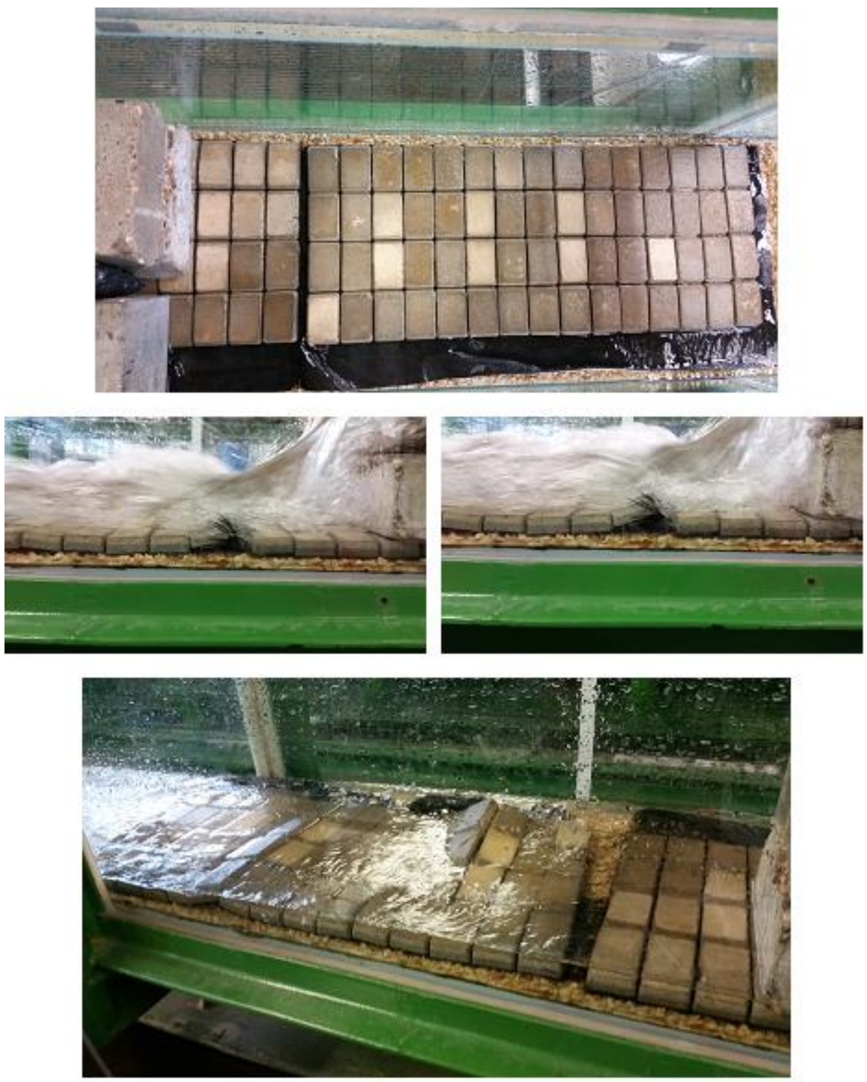

Figure 5.18 Frame to frame failure of the block mat (transition with gap)

The most interesting case, though, is the one with the overlap (without gap) between the edges of the two block mattresses. In particular, the geotextile of the second block mat was placed beneath the last row of blocks of the first block mat. The frame to frame failure in this case is depicted in Figure 5.19.

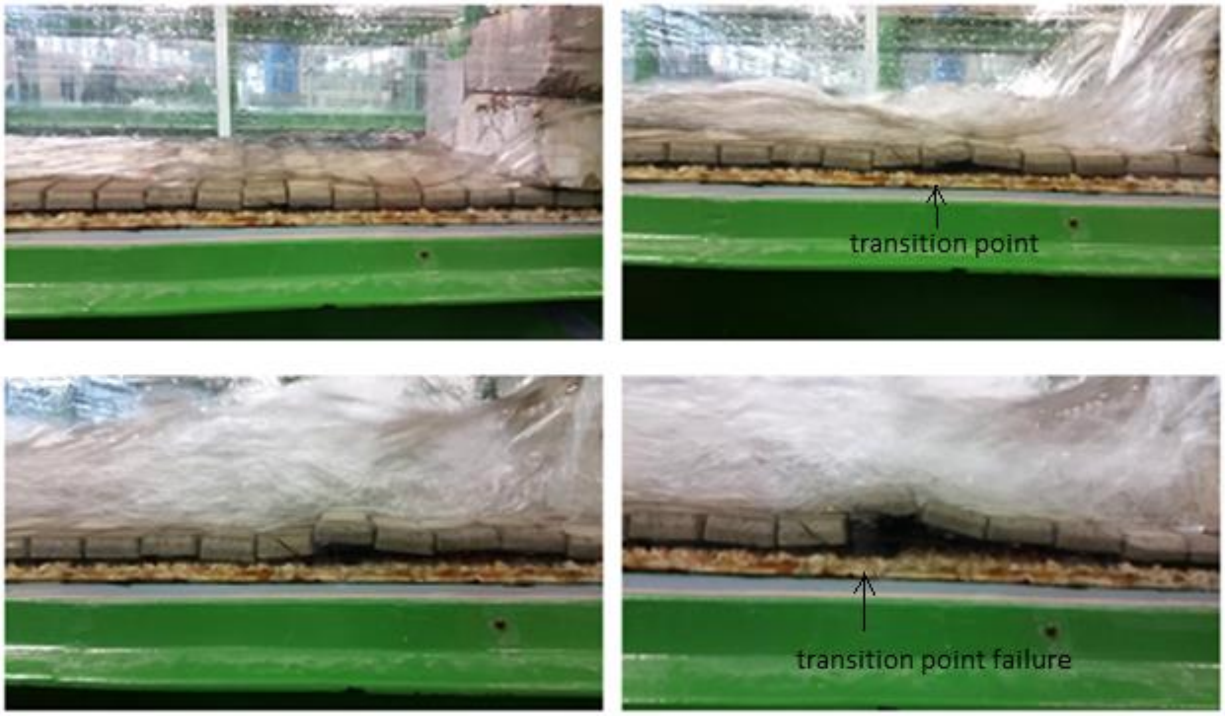

Figure 5.19 Frame to frame failure of block mat (transition with overlap)

As it can be observed from Figure 5.19, this case is more stable compared to the case with the gap. The last frame shows that only the edge of the first mat displays a significant movement up and down (which is considered to be failure). The reason is the placement of the geotextile of the second mat under the last row of blocks of the first mat. Particularly, by making this configuration (overlap) in the transition point of the block mattresses, it is difficult for the flow to pass beneath the geotextile of the second block mat and turn it over. In that way, the second block mattress, which in the previous case was totally taken away by the flow (a failure similar to the one of the block mats in the first test series), is now protected. On the other hand, the movement of the last row of blocks of the first mat is considerably larger than the one observed in the second test series (for an open-end edge). This can be explained by the fact that the flow was hitting in the first row of blocks of the second mat causing an upward flow under the last row of blocks of the first mat, which eventually was leading to a greater movement (up and down).

5.4 Summary

Having said this, the main conclusions that can be derived by these three test series are:

- A totally unprotected upstream edge (free) is very sensitive to turbulent conditions (first test series)

- According to the qualitative results of the first test series, the sudden failure of the block mat seems to be very 'brutal' (first test series)
- A 'fixed' upstream edge enhances the stability of the block mat (second test series)
- The levels of turbulence seem to be more important for the stability of block mats compared to the mean value of the velocity close to the mat (second test series)
- Pilarczyk's formula tends to underestimate the 'strength' of the block mats considering the edge blocks (last blocks), whereas it seems to overestimate the 'strength' of the block mattresses considering the middle blocks (continuous layer) (second test series)
- The stability of block mats may also be a fatigue problem (connection between geotextile and blocks needs to checked), which is considered to be very risky and for that reason any vibrations should be avoided (second test series)
- The frequency of mat's vibrations is extremely important (second test series)
- The calculated turbulence magnification factor (α) for edge-block and middle-block failure is around -2.5 and -3.5 respectively. Although, these values are not realistic, because α-values should be by definition positive (second test series)
- In case of a transition point, an overlap (zero gap) between the two block mattresses is more stable compared to a transition point with a gap (third test series)

6. Follow-up program

The results (Chapter 5) from the first approach (experiment) on the stability of block mats are considered to be very promising. For this reason, a follow-up program consisting of more detailed experiments is necessary, in which all the directions and the paths that were found during this project will be followed and taken into account. As it was mentioned in the previous chapters, this project is one of the first attempts in order to understand and deal with the processes that affect the stability of block mats. However, after this project there are certain paths that should be followed in order to achieve the general goal of the optimization of the stability formulas. Hence, this chapter refers to the next steps that need to be made by utilizing fully and effectively this project's knowledge.

6.1 Cases

As analysed previously, there are two main cases regarding the stability of block mats that arose during this project's experiments. These are presented in the two following Figures (6.1 and 6.2).

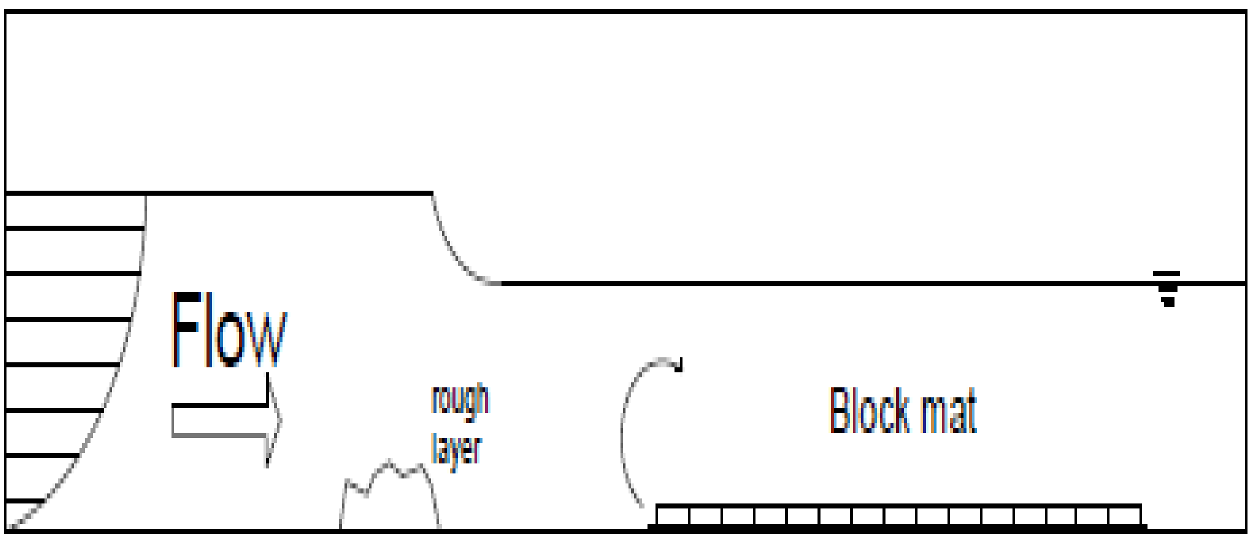

Figure 6.1 Case 1-Free to move block mat under turbulent flow

The first case, as presented in Figure 6.1, has to do with the stability of a totally free (without fixed edges) to move block mat under turbulent conditions. Specifically, this case was examined qualitatively (first test series) and there are some videos showing that any 'disturbances' on the flow that increase the levels of turbulence are mostly responsible for the overturning of the upstream edge of the block mat, as depicted by the arrow in Figure 6.1. Unfortunately, there were not measurements during these test series, since the Electromagnetic sensor (EMS), which was used as the measurement equipment of this first approach (experiments on block mats) could be damaged due to the significant movement of the block mat.

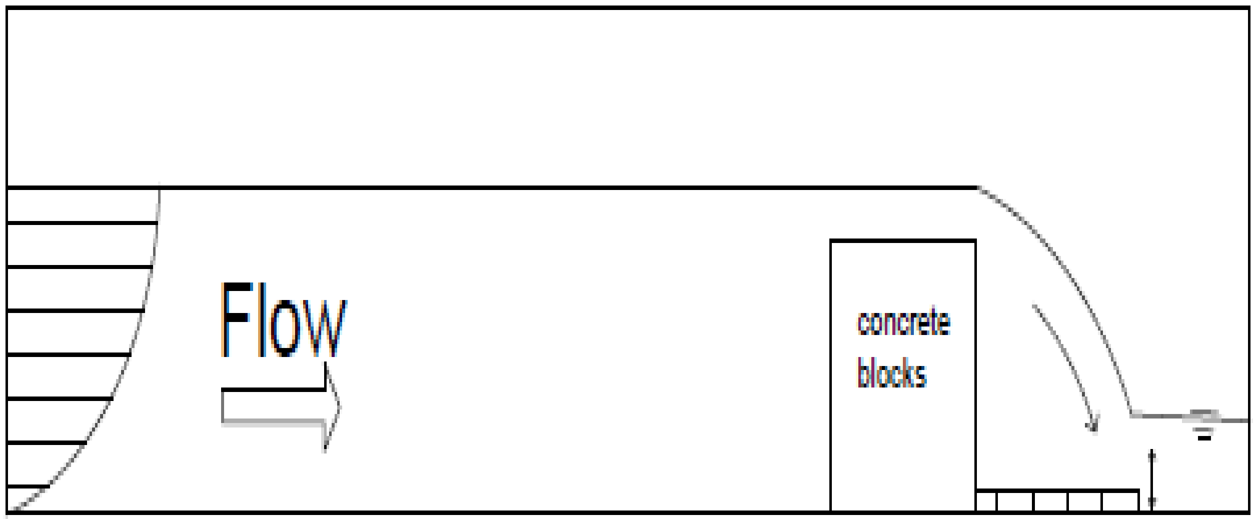

Figure 6.2 Case 2-Turbulent flow ‘hitting’ the block mat’s edge

In the second case (second test series) apart from the videos, there are also some measurements that indicate the trends of the behaviour of the block mat, when the flow is ‘hitting’ the edge of the mat, which causes the up and down movement of the block mattress as presented by the arrows in Figure 6.2. These measurements, which were analysed previously, refer mostly before the failure and at the failure of the block mat. In addition, the fact that the EMS interrupts the flow while measuring, has as consequence that these measurements cannot be so precise and detailed, but they represent on a good level the trends regarding the stability of the block mats.

Objective of the follow-up program is to examine in a more quantitative way these two cases and lead to accurate results that can be used for the optimization of the current stability formulas. For this reason, this chapter aims to the analysis and the description of these experiments that need to be done taking into account the knowledge acquired during the first attempt of dealing with the stability of block mats in practice.

6.2 Goal

It is worth mentioning that before ‘organising’ each case and experiment, it is necessary to keep in mind the final goal of all these experiments and tests (that have already be done or that need to be done in the future), which is the better interpretation of the behaviour of block mats either by design guidelines or by stability equations.

Hence, the goal is to derive a stability formula for block mattresses like the ones for loose stones under non-uniform flows that are analysed in Chapter 3. The general form of this stability parameter is:

$$\Psi = \frac{\bar{u}^2 + 2\overline{u\acute{u}}}{\Delta g d} \tag{6.1}$$

As it can be observed, there is a need for precise measurements of different combinations of velocity and turbulence at the moment of failure of the block mats in order to conclude to a stability parameter like the one presented in Equation 6.1. In addition, assuming that the levels of turbulence near the bed mainly influences the stability of the block mattress and this effect of turbulence is decreased close to the surface, it is important to use a weighting function for the influence and 'distribution' of turbulence above the block mat. Moreover, there is a need to test different block thicknesses in order to interpret how the block thickness contributes to the block mat's stability. These measurements should be the result of experiments that will be done regarding the two different cases (paths) that were mentioned before and will be analysed further below.

6.3 Case 1

The first case, which is presented in Figure 6.1, has as main failure mode the overturning of the upstream edge of the block mattress mostly due to turbulent flow conditions. In order to create the suitable conditions for the failure of the block mat, two different types of experiments are suggested. Specifically, the first type has to do with non-uniform and decelerating flow, which can be achieved by creating an expansion in the channel. The second suggestion is about the placement of the block mat downstream of a sluice gate, where accelerating non-uniform flow occurs. Both of these two configurations are suggested due to the following reasons:

- representation of reality (flow and conditions that exist in real constructions)(not just random stones for turbulence)
- there is the possibility for creating various combinations of velocity and turbulence

Particularly, one of the most important aspects of these experiments is to be able to create different combinations of turbulence and velocity. For that reason, the case with the expansion of the channel is definitely very suitable. Similar experiments were done on the stability of loose stones under non-uniform flow by Hoan (2008). A sketch of the configuration is presented in Figure 6.3, in which it is obvious that various combinations of velocity and levels of turbulence can be obtained by changing the expansion length (expansion angle)(Hoan, 2008). As it is shown in the sketch, the width of the flume is narrowed in the upstream part and the expansion is made in the location where the block mattress is placed.

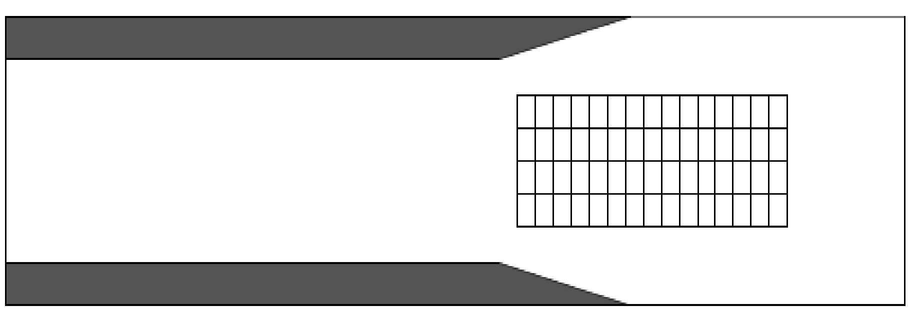

Figure 6.3 Plan view of the experimental configuration (expansion)

Regarding the experiment with the flow under the sluice gate, a sketch of this suggested experimental configuration is presented in Figure 6.4. As it can be observed different water depths downstream of the gate can be achieved by simply changing the level of the sluice gate. Furthermore, different locations where the block mat is placed downstream of the sluice gate should be examined (like beneath the hydraulic jump, etc.) so that different combinations of velocity and turbulence can be obtained.

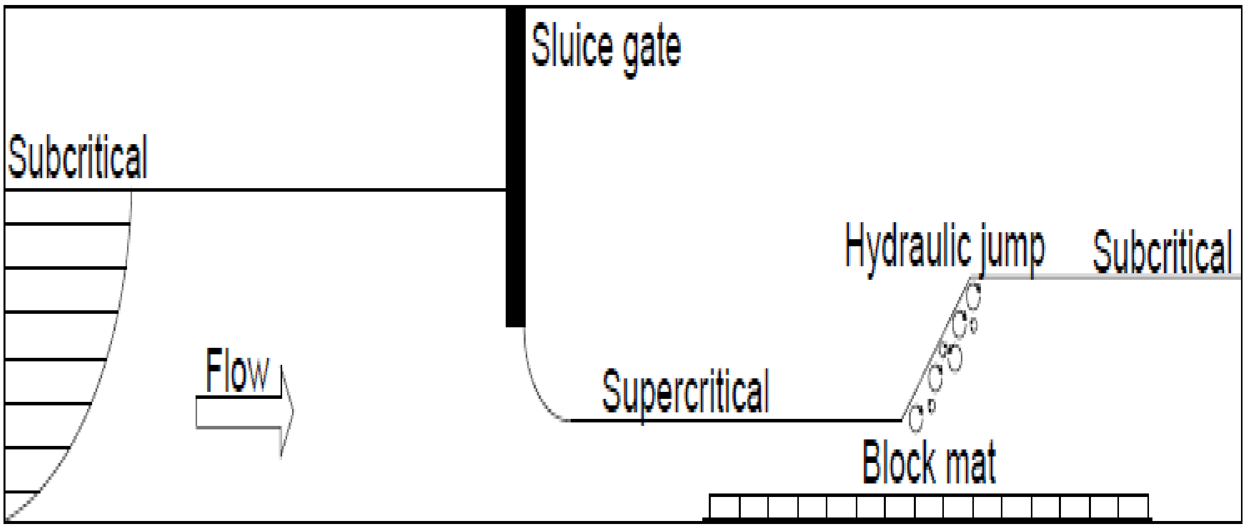

Figure 6.4 Experimental configuration of the sluice gate

6.4 Case 2

The second case which is presented in Figure 6.2 has as main failure mode the frequent up and down movement of the block mattress (usually at the downstream edge or middle of the block mat). For this case, there are also two suggestions for the follow-up program on the stability of block mats. In particular, the first suggestion is about the flow over a weir with the block mattress placed downstream of it and the second suggestion refers to a backward-facing step. Both of these two suggestions have the advantages that:

- can be easily applied in the lab
- represent real constructions
- 'allow' different combinations of velocity and turbulence to be checked

First of all, the case with the flow over the weir has many similarities with the experiments that were done during this project. The only basic difference is that in this project rough stones and large concrete blocks were placed upstream of the block mat in a random configuration in order to create turbulent conditions, whereas a flow over a weir has specific characteristics and can be regarded as a real life's situation. In addition, different combinations of velocity and levels of turbulence can be achieved by simply changing the dimensions of the crest (especially the height) and placing the block mat in different locations downstream. A sketch of this experimental configuration is presented in Figure 6.5.

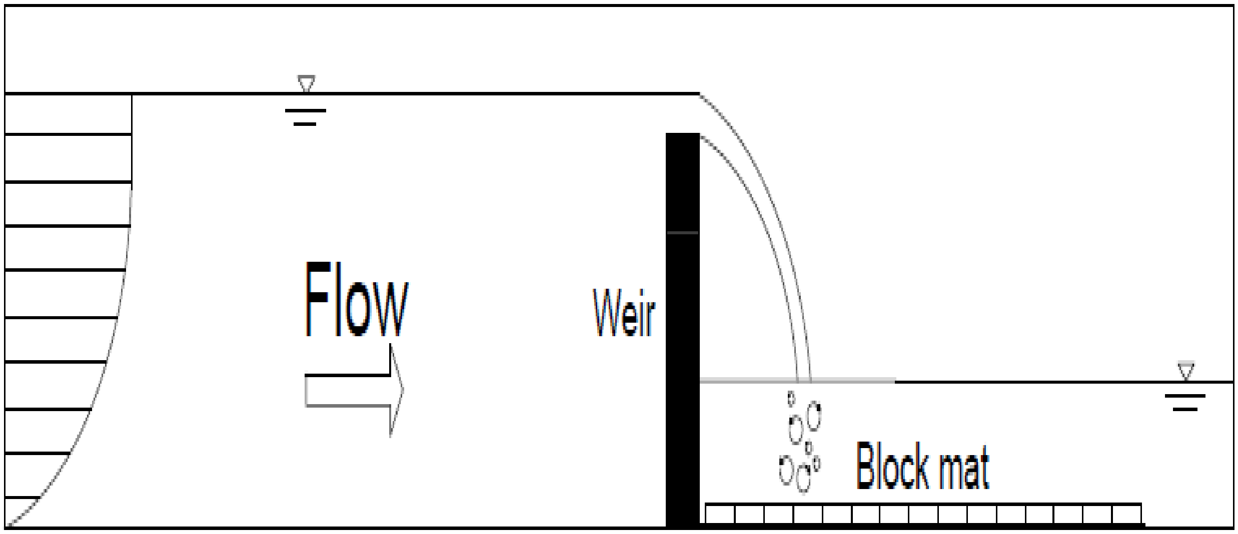

Figure 6.5 Experimental configuration of the weir

Regarding the second suggestion of the backward-facing step, it is worth mentioning that in this case it is relatively easy to find various combinations of turbulence and velocity. Moreover, it is of major importance to keep in mind that at distance 6 or 7 times the height of the step there is the reattachment point where the maximum levels of turbulence exist. For that reason by placing the block mattress at different locations downstream of the step, it is possible to examine the influence of turbulence and velocity on the stability of the block mat. Furthermore, different heights of the step can be used in order to achieve the desired variety between velocity and turbulence. Another aspect that needs to be taken into account is that in order to keep a certain water level in the flume there is a need to use the gate at the end of the flume. In that way, the water depth in the flume is controlled. In Figure 6.6 a sketch for this experimental configuration is presented.

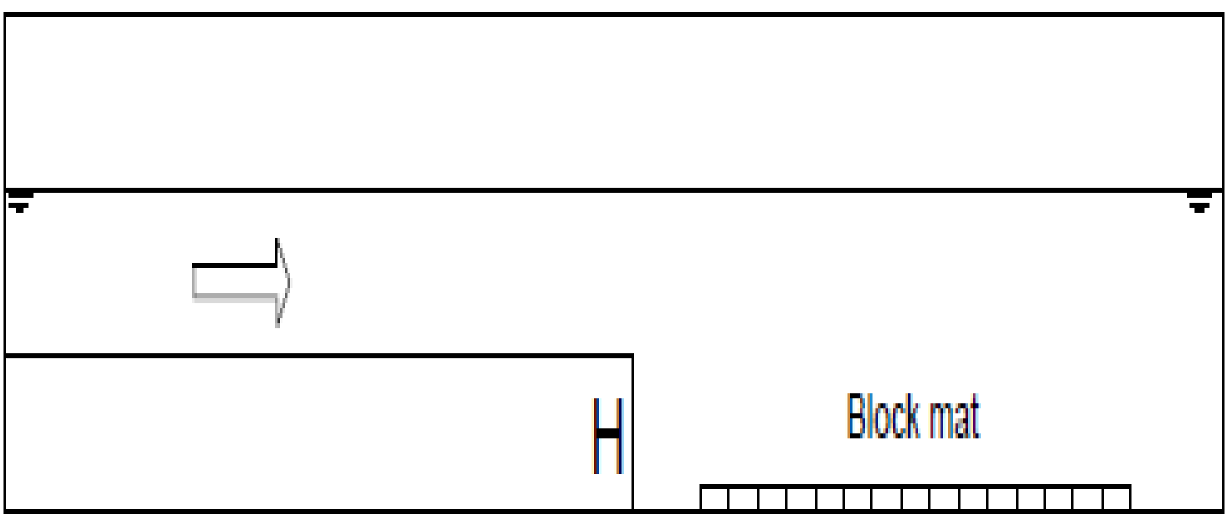

Figure 6.6 Experimental configuration of the backward-facing step

In addition, in the following Figure (6.7) the characteristics of the flow next to the step is shown, in which it is obvious that there are locations downstream of the step with different combinations of velocity and turbulence.

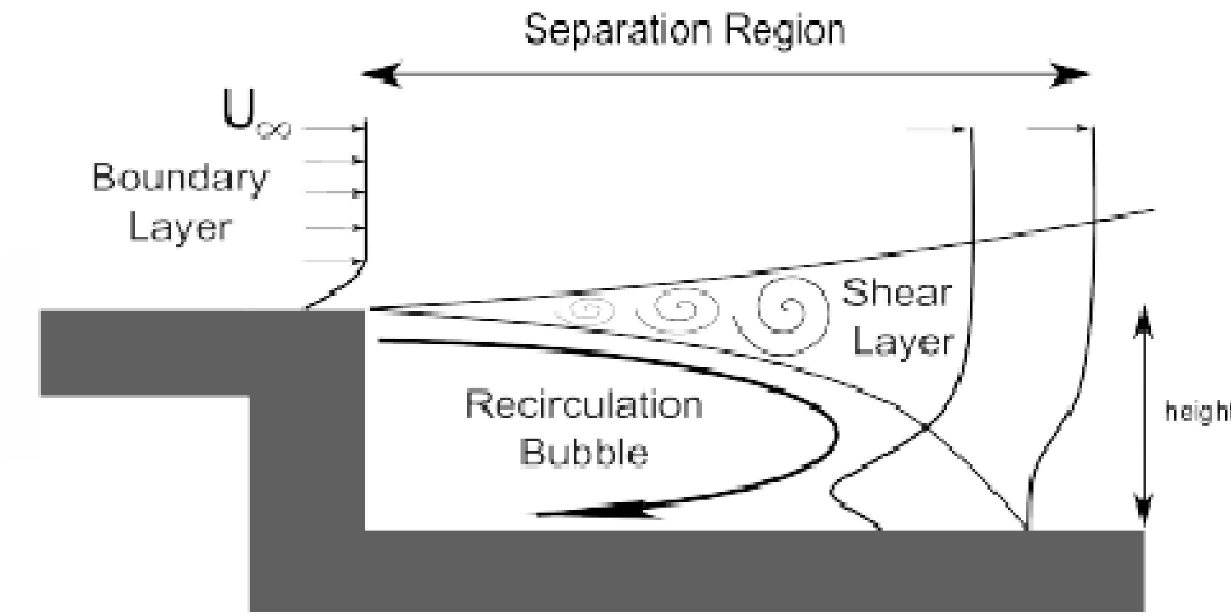

Figure 6.7 Backward-facing step (Gautier, N., Aider, J.-L., 2014)

6.5 Measurements – Measurement equipment

Regarding the measurements of the experiments, there are three basic points that should be selected:

- location of measurements
- the measurement equipment that should be used
- frequency of the hydrodynamic measurements

First of all, the location of the measurements should be chosen according to the expected failure. The main failure mode for almost all the cases, which are described above, is the overturning of the edge's mat. Hence, the measurements of the velocity should be taken close to the block mat's edge.

Another important aspect that needs to be taken into account in order to select the proper measurement equipment is the fact that the measurements should be synchronised with the moment of failure. In other words, it is very important to be able to distinguish the moment of failure in the measurements, because in that way it is easier to understand what exactly caused this failure. This can be done in two different ways:

- use video cameras synchronised with the measurement equipment
- use measurement equipment that contains the 'visualisation' of the measurements and the flume's configuration (block mat)

The available types of measurement equipment, which are mentioned and described in detail in Chapter 3, are listed below:

- LDV (Laser Doppler Velocity meter)
- PIV (Particle Image Velocimetry)
- BIV (Bubble Image Velocimetry)
- ADV (Acoustic Doppler Velocity meter)
- EMS (Electromagnetic Flow meter)

According to the characteristics of the above mentioned types of measurement equipment, the most suitable equipment is either the PIV or the LDV. The EMS, which was used for the measurements of this project, has the disadvantage that interrupts the flow and this may not lead to accurate results especially in cases with small water depth. Consequently, PIV and LDV are supposed to be the best for this type of measurements. In case of using an LDV, there is a need to synchronise video cameras with it in order to be able to distinguish the moment of failure.

Finally, regarding the frequency of the hydrodynamic measurements, it is important to be able to get turbulent properties from the flow velocity signals. For that reason, a frequency of at least 500Hz is reasonable and should be preferred.

6.6 Synopsis

To sum up, the promising results of this project's experiments create the necessity for the next step in the research on the stability of block mattresses. Specifically, more detailed and accurate experiments should be held in the direction of the two cases that are described above:

- Case 1-Free to move block mat under turbulent flow
- Case 2-Turbulent flow 'hitting' the block mat's edge

In order to approach the first case, experiments with the expansion of the channel and flow under sluice gate are suggested, whereas for the second case the suggested experiments refer to flow over a weir and a backward-facing step. In both cases, it is of major importance to examine the role of block mat's thickness. In particular, taking into account that a stability parameter is the ratio between destabilizing forces and resistance forces, it is understandable that this ratio is not only affected by the value of destabilizing forces (flow, turbulence, etc.), but it is evenly influenced by the resistance forces. Therefore, it is to be enlightened at which extent the thickness of the block mattress contributes to the stabilizing forces and to assess the impact of different thicknesses in the flow pattern (development of boundary layer, vortices, etc.). For that reason, tests on different block thicknesses are suggested for all the aforementioned cases. In addition, tests with combinations of different velocity and turbulence are considered to be extremely important, especially for the optimisation of the stability formulas.

Finally, regarding the measurement equipment, PIV or LDV are considered to be the most suitable and it should be taken into account that the synchronisation of the equipment with video cameras, recording the behaviour of the block mat, is necessary. The frequency of the hydrodynamic measurements should be at least 500Hz in order to be able to obtain turbulent properties.

7. Conclusions

The main objective of this Master Thesis Project was to recognise the physical processes, which cause damage to the block mattresses in order to enhance the current knowledge on the stability of block mats, by analysing the literature background and setting up some experiments as a first approach. The main conclusions that have been derived are presented below:

- A totally free to move block mattress, which is subjected to turbulent flow, has as failure mode the overturning of the upstream open-edge. In addition, by the time that the flow manages to overturn the edge of the mat and pass beneath the geotextile, the block mat is shifted downstream with a 'wavy' motion. Moreover, according to the recorded videos, the levels of turbulence seem to be more important compared to the magnitude of the velocity. Hence, a protected or somehow 'fixed' upstream edge is suggested in order to enhance the stability of the block mat.
- The levels of turbulence are of major importance, since in the measurements that were done during the experiments it was proved that failure occurs when there is excessive turbulence even with low values of velocity. Therefore, the levels of turbulence are more crucial for the stability of the block mats compared to the flow velocity.
- According to the comparison that was done between the application of Pilarczyk's equation and the experimental measurements, Pilarczyk's formula tends to underestimate the 'strength' of the block mats considering the edge blocks (last blocks), whereas it seems to overestimate the 'strength' of the block mattresses considering the middle blocks (continuous layer). The main reason for this difference in Pilarczyk's approach between edge blocks and middle blocks has to do with the assumptions for the value of the stability factor ϕ_{sc}.
- Another interesting and important conclusion is that the stability of the block mats may also be a fatigue problem, since there were some vibrations of the blocks that were noticed during the experiments. Although, vibrations should be avoided in any case, because this situation is considered to be risky and undesirable for the stability of block mats.
- In case of a transition point, an overlap (zero gap) between the two block mattresses is more stable compared to a transition point with a gap. Particularly, by making this configuration (overlap) in the transition point of the block mattresses, it is difficult for the flow to pass beneath the geotextile of the second block mat and turn it over.

8. Recommendations

Taking into account that this Master Thesis Project is one of the first attempts in order to approach the stability of block mattresses, there are further research-studies that arose and are recommended in this section. Most of these recommendations are related to real life structures so that a design guideline for block mats can be derived. In addition, some of these recommendations refer to complementary measurements in order to get a sufficient number of data.

- It is strongly recommended to test the stability of block mats, which are placed downstream of a backward-facing step for different combinations of velocity and turbulence. In that case the downstream part (edge) of the block mat is mainly affected.
- Moreover, tests on block mats that are placed downstream of a channel's expansion or a sluice gate are recommended. Specifically, this case refers mostly to the stability of the upstream edge of the block mattress.
- Based on the qualitative results of the first test series, which present a 'brutal' failure, it is recommended to derive (propose) a safety factor (by the described experiments in Chapter 6), which will take into consideration this harmful type of failure.
- In addition, it is of major importance to test different block thicknesses of block mattresses in order to be able to interpret the degree at which the stability of a block mat is affected by the block thickness.
- Apart from the tests on different thicknesses, it is worth mentioning that different shapes or even types of connection between the blocks and the geotextile should be examined in order to find the optimum solution or even come up with new design methods for block mats.
- The calculated (in the second test series) turbulence magnification factor (α) for edge-block and middle-block failure is around -2.5 and -3.5 respectively. Although, these values are not realistic, because α-values should be by definition positive. As it is already mentioned, the evaluation of the experimental data from all these tests can lead to the derivation of a new stability formula, in which different combinations of turbulence, velocity and block thickness are taken into account. For that reason, there is a need for sufficient number of data and accurate measurements.
- Taking into consideration the observations regarding the vibrations of the block mat, it is strongly recommended to examine the block mats for fatigue. Particularly, it is suggested to check the behaviour of a block (connected with a geotextile under it) under vibrations in a vibrator. The tearing of the geotextile should also be taken into account as a failure mode for further research.

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Appendix A - Experimental measurements

Measurements											
No. of Test	Setup-Configuration (measuring point)	Duration	Vx (mean value)	Standard Deviation of Vx	Turbulence intensity r_x	Vz (mean value)	Standard Deviation of Vz	Turbulence intensity r_z	Discharge	Condition	Comments
Test01	One layer of rough stones and concrete blocks placed above the block mat in a distance of **five** open blocks from the open-end edge (last block of mat)	80.63 sec	1.2221 m/sec	0.1063 m/sec	0.087	0.2868 m/sec	0.1027 m/sec	0.084	0.043 m^3/sec	Stable	first measurements to learn the equipment (all of them are not so reliable, especially Test02 which contains error in Vz)
Test02	Two layers of rough stones and concrete blocks placed above the block mat in a distance of **five** open blocks from the open-end edge (last block of mat)	124.15 sec	0.7080 m/sec	0.3691 m/sec	0.521	0.6677 m/sec	0.2602 m/sec	0.368	0.0411 m^3/sec	Failure	
Test03	Two layers of rough stones and concrete blocks placed above the block mat in a distance of **five** open blocks from the open-end edge (last block of mat)	121.59 sec	0.6988 m/sec	0.3265 m/sec	0.467	0.7094 m/sec	0.3229 m/sec	0.462	0.0399 m^3/sec	Failure	
Test04	Two layers of rough stones and concrete blocks placed above the block mat in a distance of **five** open blocks from the open-end edge (last block of mat)	126.07 sec	0.9204 m/sec	0.3037 m/sec	0.329	0.6464 m/sec	0.2331 m/sec	0.253	0.0347 m^3/sec	Stable	second test series
Test05	Two layers of rough stones and concrete blocks placed above the block mat in a distance of **five** open blocks from the open-end edge (last block of mat)	123.51 sec	0.7910 m/sec	0.3033 m/sec	0.383	0.6456 m/sec	0.2621 m/sec	0.331	0.0371 m^3/sec	Failure	second test series

Measurements											
No. of Test	Setup-Configuration (measuring point)	Duration	Vx (mean value)	Standard Deviation of Vx	Turbulence intensity r_x	Vz (mean value)	Standard Deviation of Vz	Turbulence intensity r_z	Discharge	Condition	Comments
Test06	Two layers of rough stones and concrete blocks placed above the block mat in a distance of **six** open blocks from the open-end edge (last block of mat)	123.51 sec	0.7584 m/sec	0.2886 m/sec	0.381	0.6031 m/sec	0.2706 m/sec	0.357	0.0438 m^3/sec	Failure	second test series
Test07	Two layers of rough stones and concrete blocks placed above the block mat in a distance of **six** open blocks from the open-end edge (last block of mat)	138.23 sec	0.9927 m/sec	0.3636 m/sec	0.366	0.6640 m/sec	0.3148 m/sec	0.317	0.0379 m^3/sec	Stable	second test series
Test08	Two layers of rough stones and concrete blocks placed above the block mat in a distance of **six** open blocks from the open-end edge (between 3rd and 4th block)	142.07 sec	0.7664 m/sec	0.1153 m/sec	0.15	0.8484 m/sec	0.1455 m/sec	0.19	0.0379 m^3/sec	Failure	second test series
Test09	Two layers of rough stones and concrete blocks placed above the block mat in a distance of **six** open blocks from the open-end edge (between 3rd and 4th block)	128.63 sec	0.8787 m/sec	0.0837 m/sec	0.095	0.7303 m/sec	0.1061 m/sec	0.121	0.0339 m^3/sec	Stable	second test series
Test10	Two layers of rough stones and concrete blocks placed above the block mat in a distance of **seven** open blocks from the open-end edge (4th block of the mat)	128.63 sec	0.8414 m/sec	0.2321 m/sec	0.276	0.7413 m/sec	0.1657 m/sec	0.197	0.0354 m^3/sec	Stable	second test series
Test11	Two layers of rough stones and concrete blocks placed above the block mat in a distance of **seven** open blocks from the open-end edge (4th block of the mat)	124.79 sec	0.6359 m/sec	0.1728 m/sec	0.271	0.6633 m/sec	0.1389 m/sec	0.218	0.0419 m^3/sec	Failure	second test series

Measurements											
No. of Test	Setup-Configuration (measuring point)	Duration	Vx (mean value)	Standard Deviation of Vx	Turbulence intensity r_x	Vz (mean value)	Standard Deviation of Vz	Turbulence intensity r_z	Discharge	Condition	Comments
Test12	Two layers of rough stones and concrete blocks placed above the block mat in a distance of **eight** open blocks from the open-end edge (between 4th and 5th block)	133.11 sec	0.6239 m/sec	0.2471 m/sec	0.396	0.6119 m/sec	0.1670 m/sec	0.268	0.0416 m^3/sec	Failure	second test series
Test13	Two layers of rough stones and concrete blocks placed above the block mat in a distance of **eight** open blocks from the open-end edge (between 4th and 5th block)	125.43 sec	0.9427 m/sec	0.2508 m/sec	0.266	0.6102 m/sec	0.1484 m/sec	0.157	0.0349 m^3/sec	Stable	second test series
Test14	Two layers of rough stones and concrete blocks placed above the block mat in a distance of **nine** open blocks from the open-end edge (5th block of the mat)	127.35 sec	0.7078 m/sec	0.2537 m/sec	0.358	0.5610 m/sec	0.1770 m/sec	0.25	0.041 m^3/sec	Failure	second test series
Test15	Two layers of rough stones and concrete blocks placed above the block mat in a distance of **nine** open blocks from the open-end edge (5th block of the mat)	139.51 sec	1.1124 m/sec	0.2432 m/sec	0.218	0.5602 m/sec	0.1636 m/sec	0.147	0.0337 m^3/sec	Stable	second test series
Test16	Two layers of rough stones and concrete blocks placed above the block mat in a distance of **four** open blocks from the open-end edge (last block of the mat)	129.91 sec	0.5876 m/sec	0.2989 m/sec	0.508	0.6918 m/sec	0.2043 m/sec	0.348	0.037 m^3/sec	Failure	second test series

Measurements											
No. of Test	Setup-Configuration (measuring point)	Duration	Vx (mean value)	Standard Deviation of Vx	Turbulence intensity r_x	Vz (mean value)	Standard Deviation of Vz	Turbulence intensity r_z	Discharge	Condition	Comments
Test17	Two layers of rough stones and concrete blocks placed above the block mat in a distance of **four** open blocks from the open-end edge (last block of the mat)	127.99 sec	0.8825 m/sec	0.1629 m/sec	0.185	0.6807 m/sec	0.1581 m/sec	0.179	0.031 m^3/sec	Stable	second test series
Test18	Two layers of rough stones and concrete blocks placed above the block mat in a distance of **three** open blocks from the open-end edge (last block of the mat)	142.71 sec	0.6855 m/sec	0.1343 m/sec	0.196	0.9330 m/sec	0.1270 m/sec	0.185	0.0351 m^3/sec	Failure	measuring close to surface (second test series)
Test19	Two layers of rough stones and concrete blocks placed above the block mat in a distance of **three** open blocks from the open-end edge (last block of the mat)	138.23 sec	0.4926 m/sec	0.1811 m/sec	0.368	0.7283 m/sec	0.1486 m/sec	0.302	0.0351 m^3/sec	Failure	measuring close to mat (second test series)
Test20	Two layers of rough stones and concrete blocks placed above the block mat in a distance of **three** open blocks from the open-end edge (last block of the mat)	131.19 sec	0.6558 m/sec	0.0859 m/sec	0.131	0.6005 m/sec	0.1085 m/sec	0.165	0.026 m^3/sec	Stable	measuring close to mat (second test series)
Test21	Two layers of rough stones and concrete blocks placed (**upstream**) **outside** of the block mat next to the fixed point (between 3rd and 4th block)	129.27 sec	0.6997 m/sec	0.2480 m/sec	0.354	0.5771 m/sec	0.1670 m/sec	0.239	0.0325 m^3/sec	Failure	second test series
Test22	Two layers of rough stones and concrete blocks placed above the first block mat in a distance of **five** open blocks from the open-end edge (transition point with overlap zerogap)	149.75 sec	0.8550 m/sec	0.3057 m/sec	0.358	0.5948 m/sec	0.2033 m/sec	0.238	0.0344 m^3/sec	Failure	third test series

Appendix B - Graphs ‘Velocity – Time’

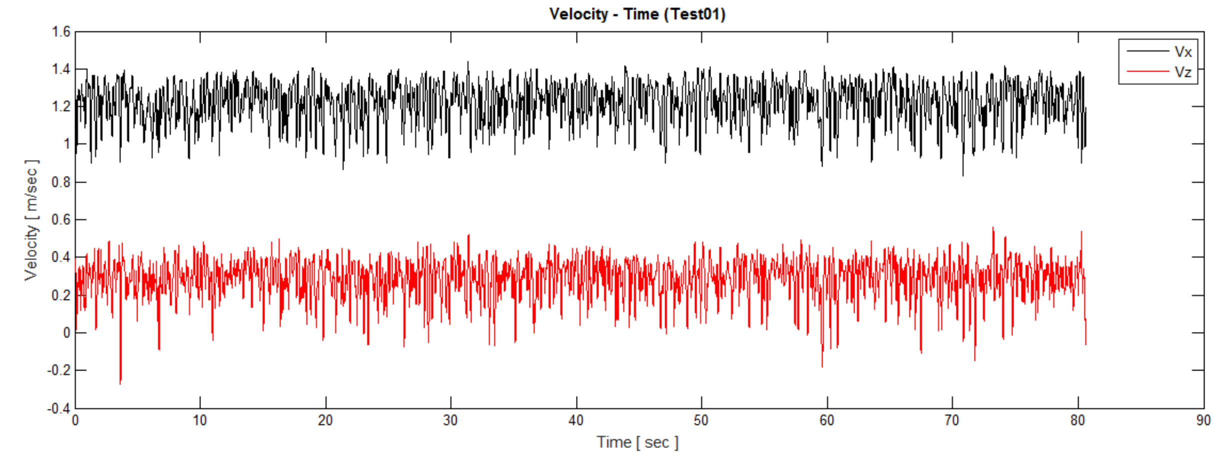

Figure B.1 Test 01

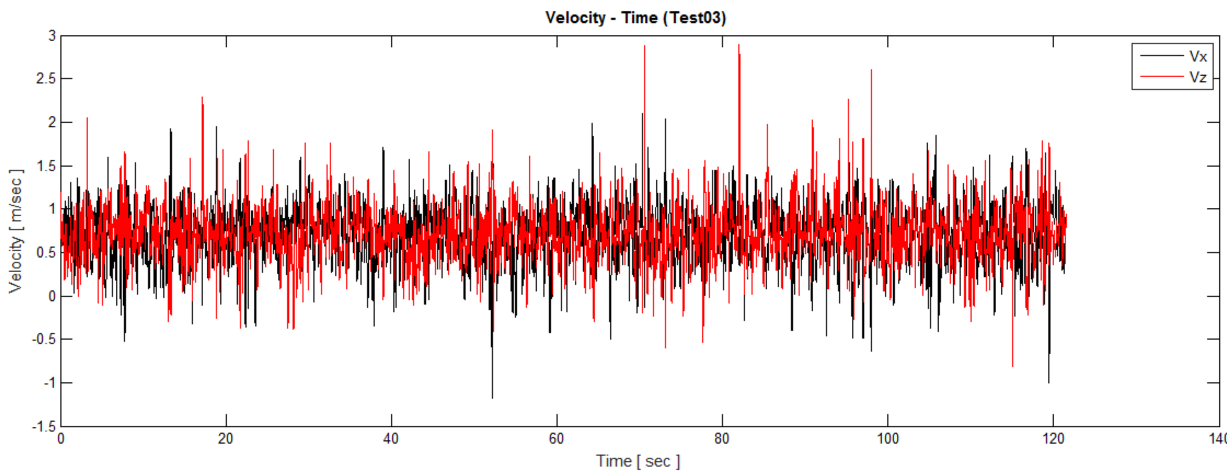

Figure B.2 Test 03

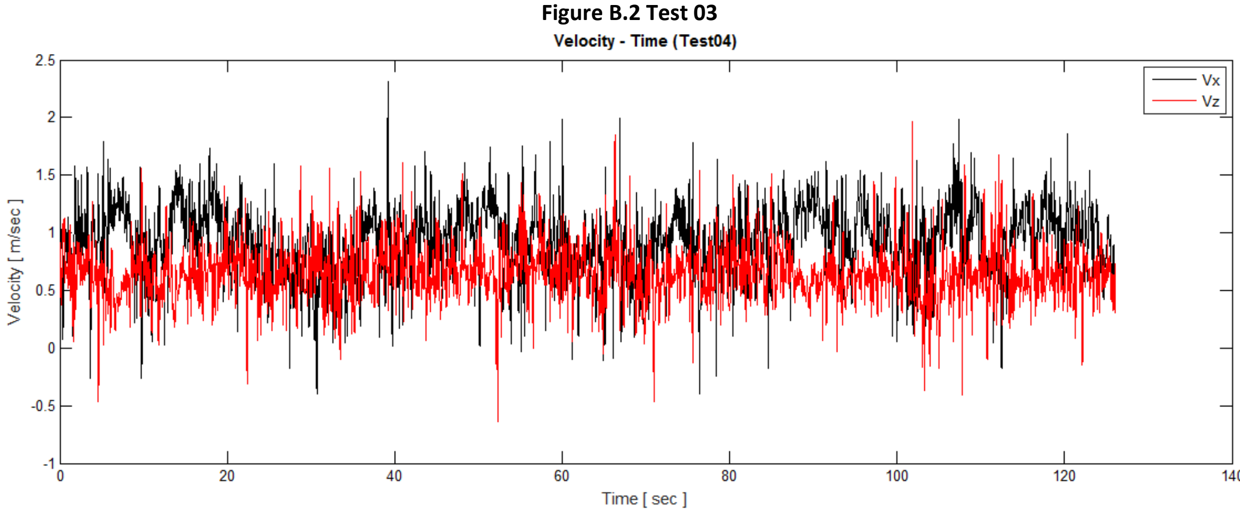

Figure B.3 Test 04

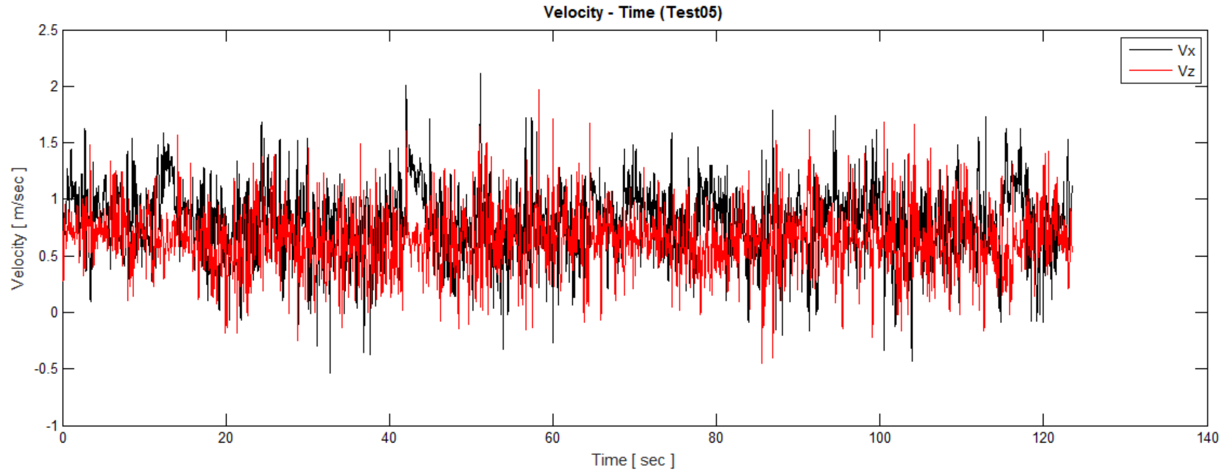

Figure B.4 Test 05

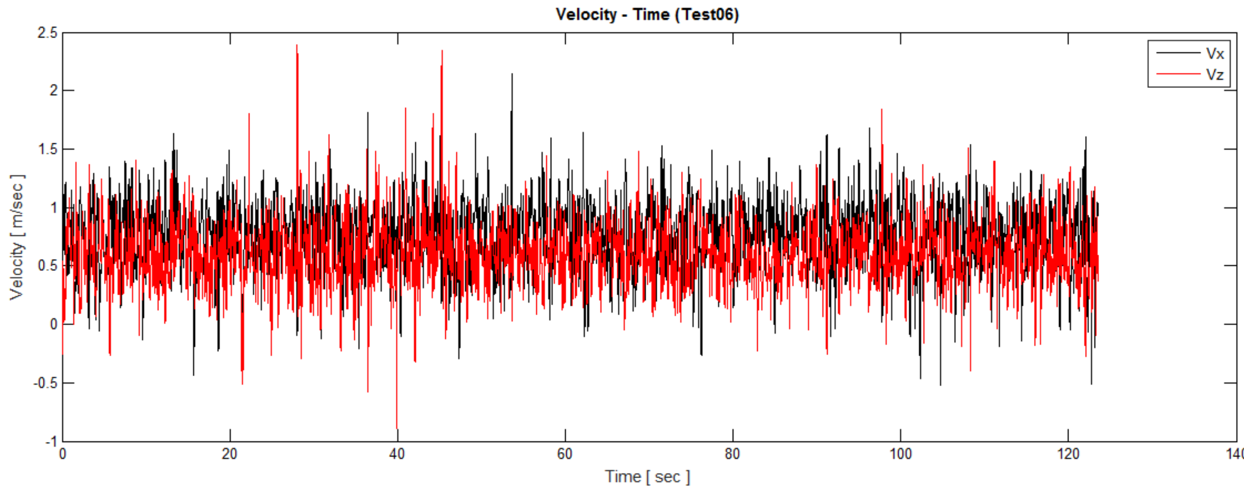

Figure B.5 Test 06

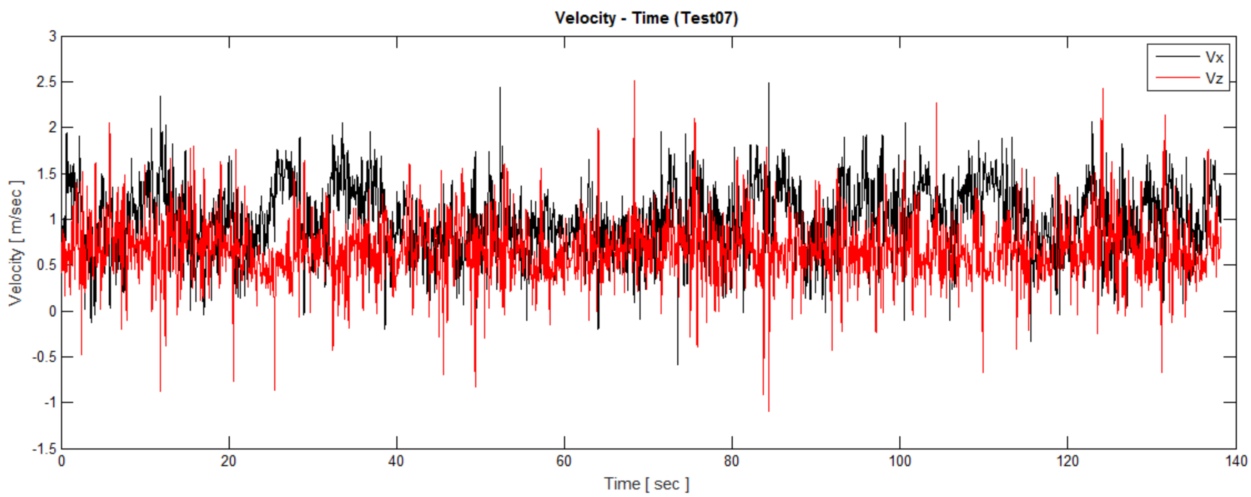

Figure B.6 Test 07

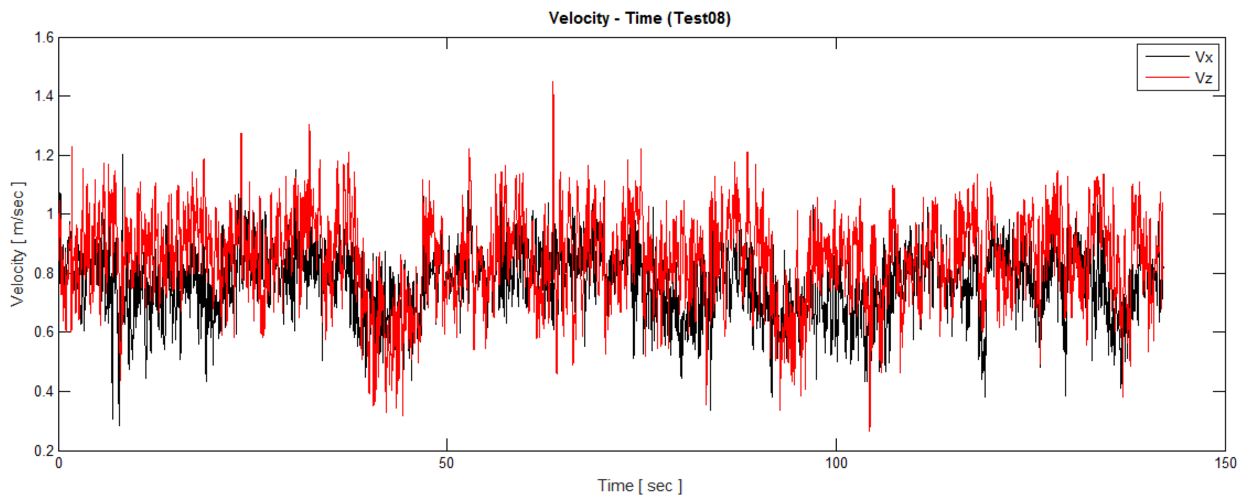

Figure B.7 Test 08

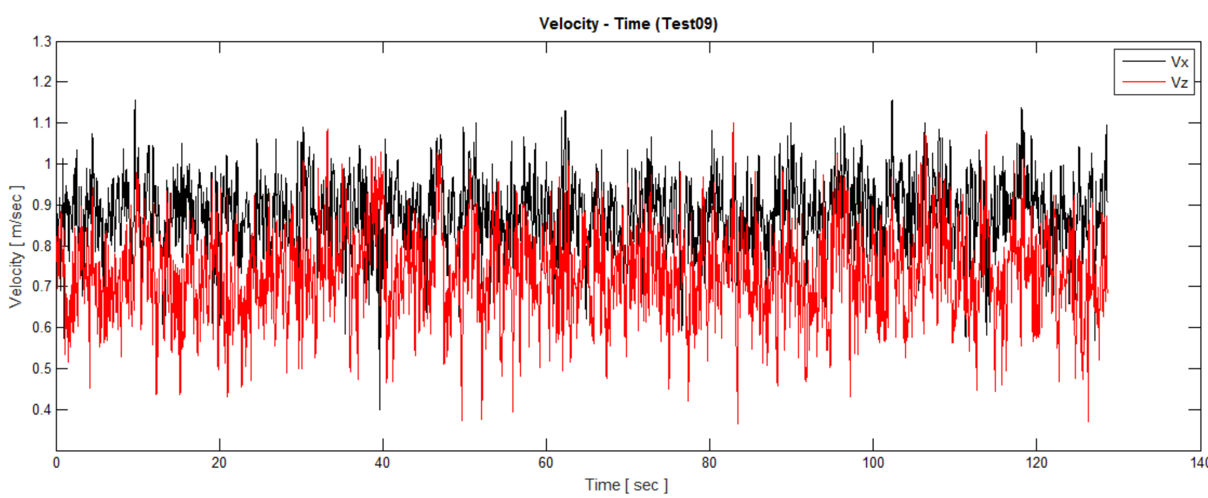

Figure B.8 Test 09

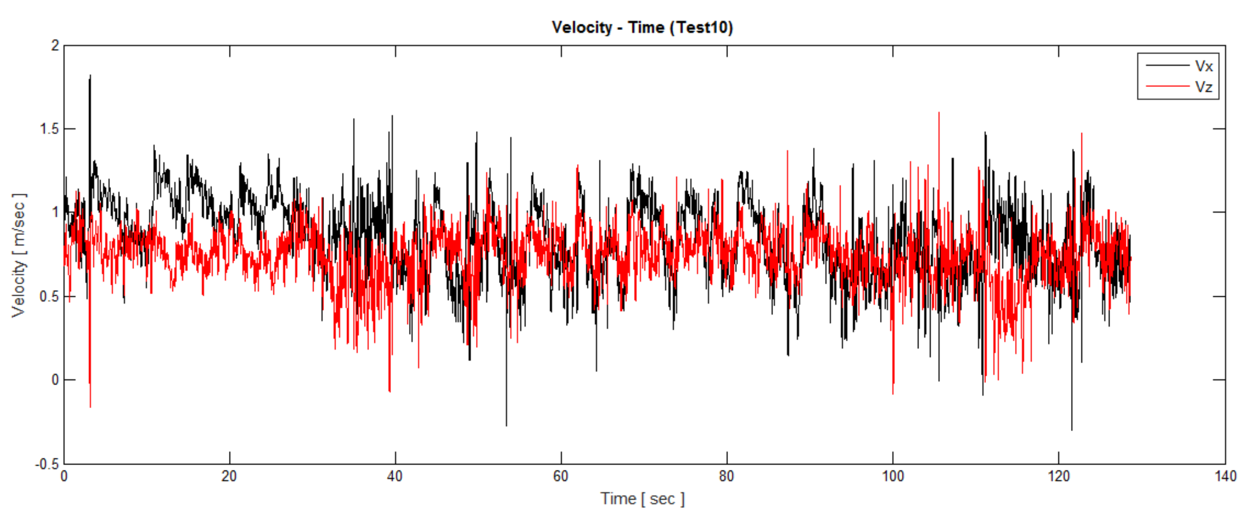

Figure B.9 Test 10

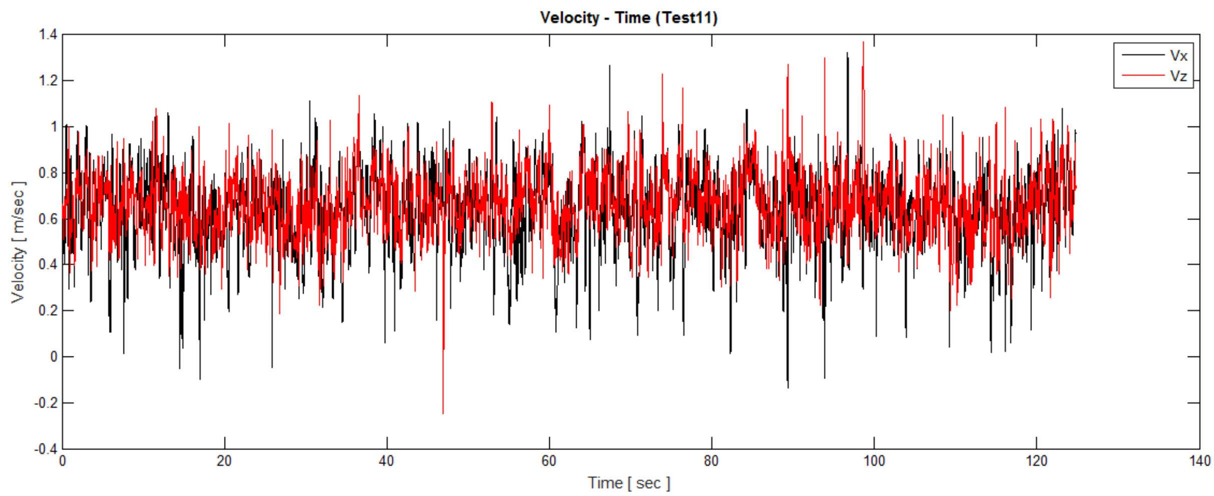

Figure B.10 Test 11

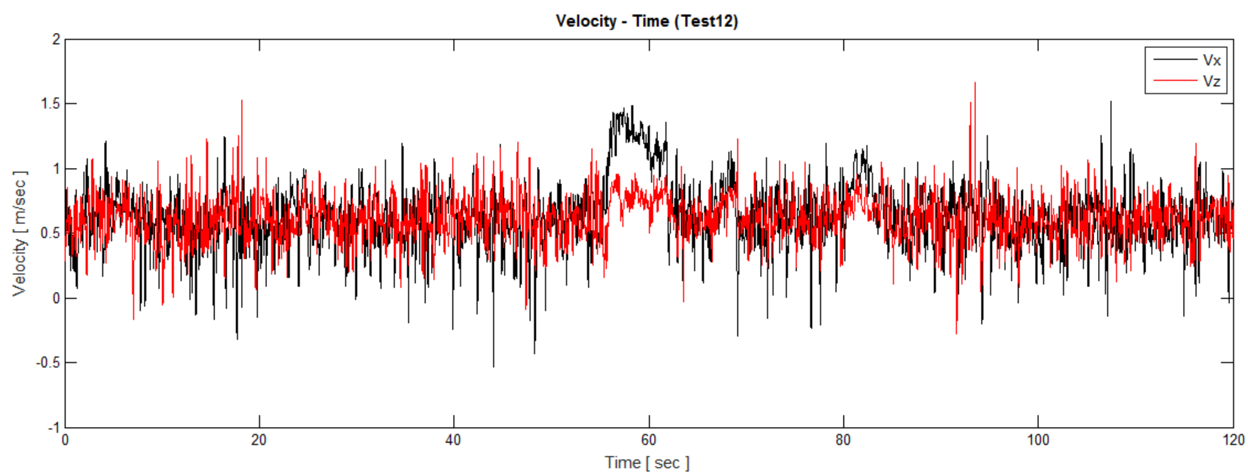

Figure B.11 Test 12

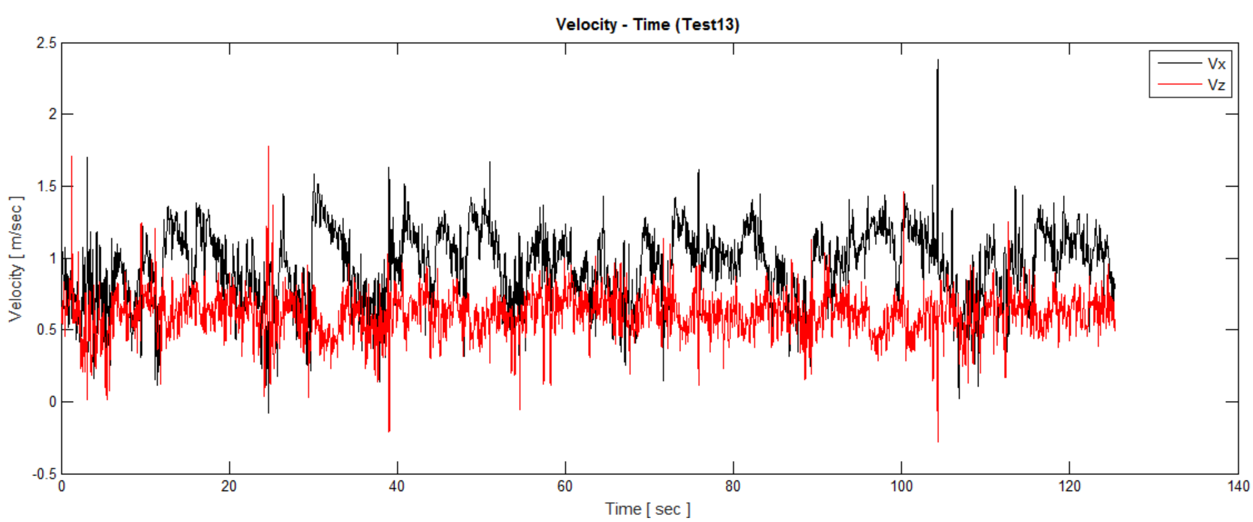

Figure B.12 Test 13

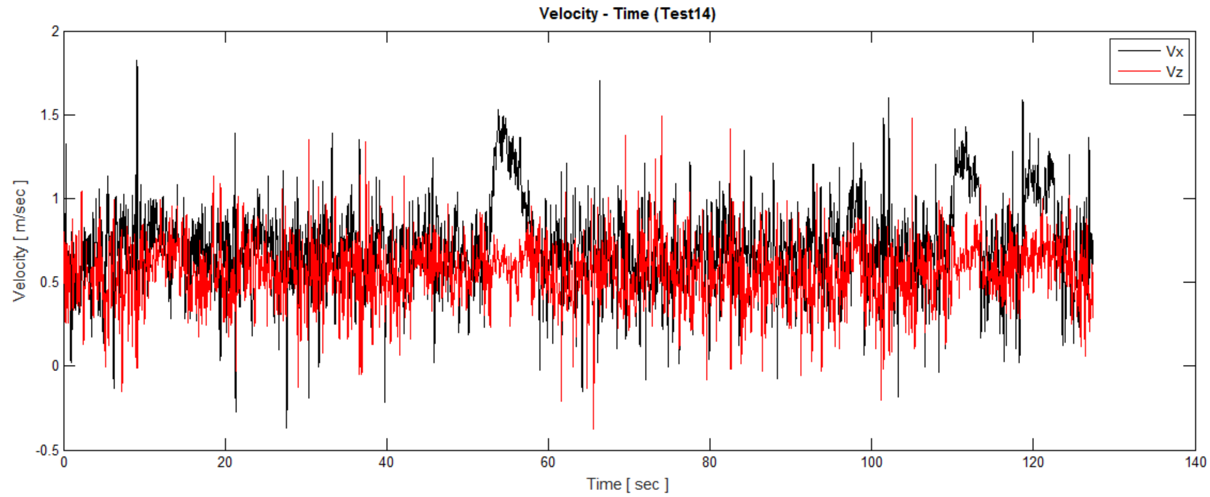

Figure B.13 Test 14

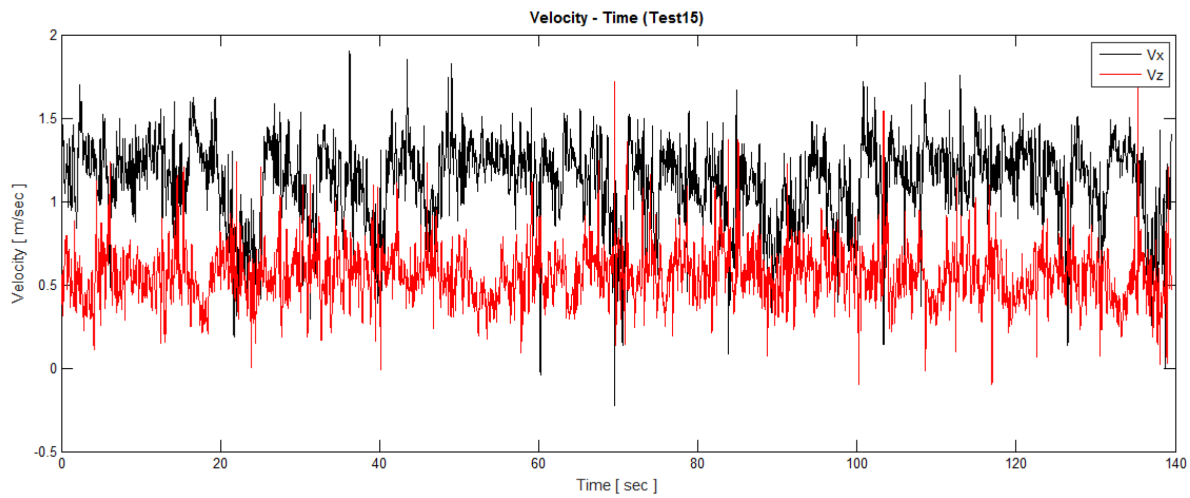

Figure B.14 Test 15

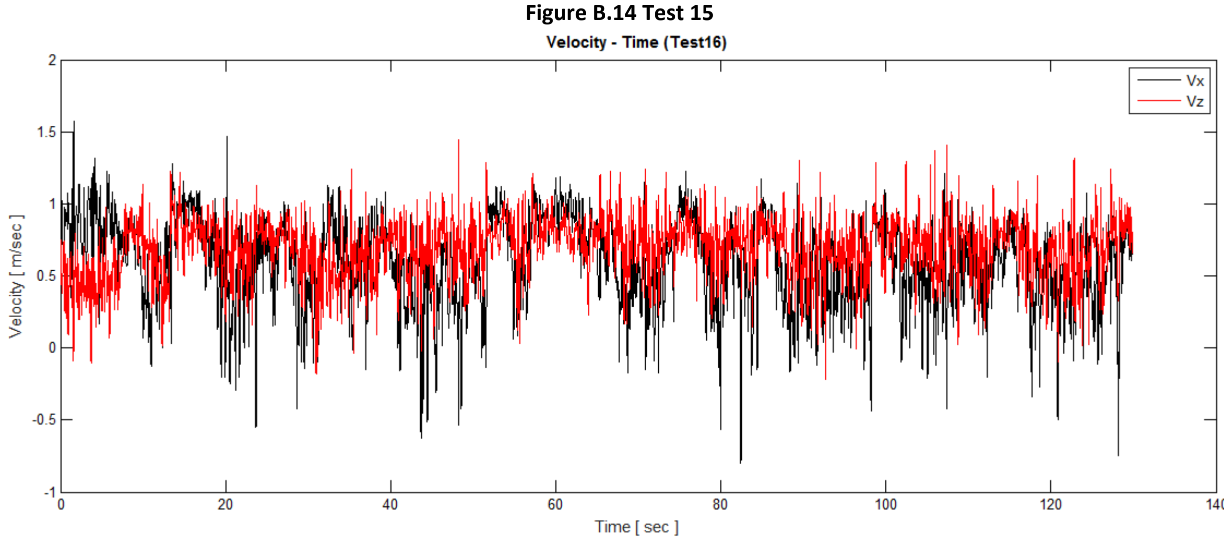

Figure B.15 Test 16

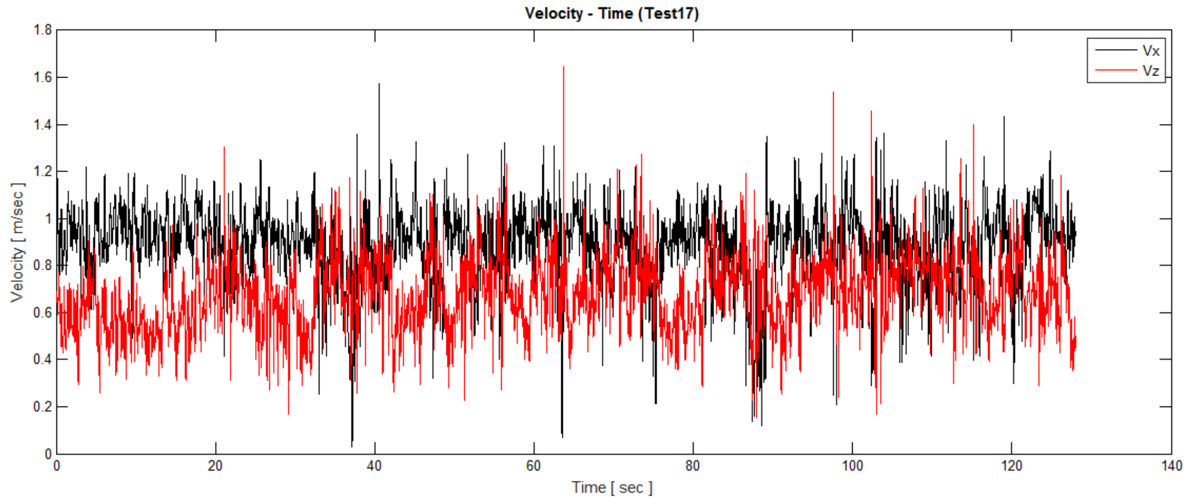

Figure B.16 Test 17

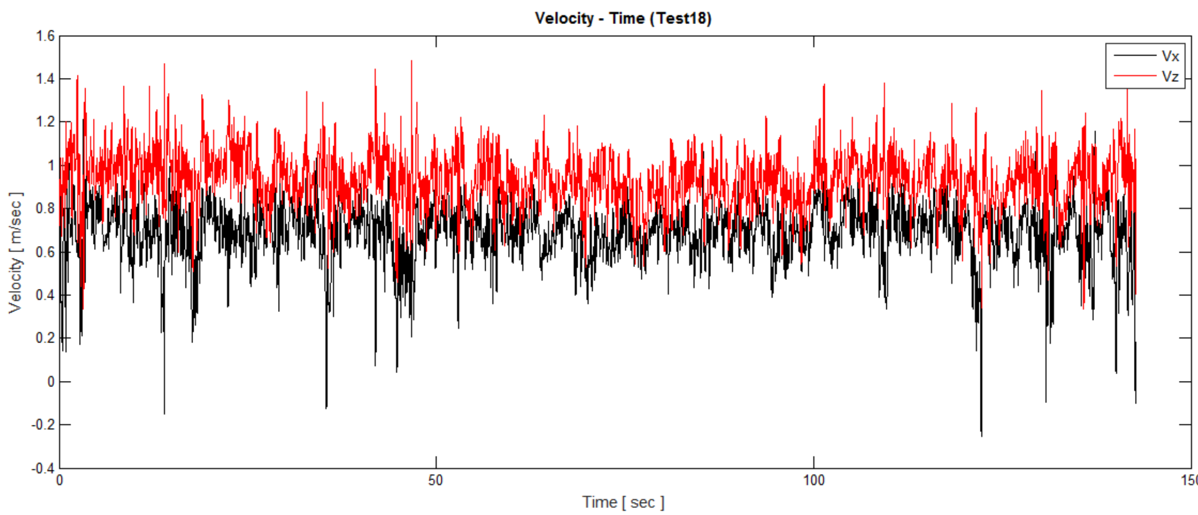

Figure B.17 Test 18

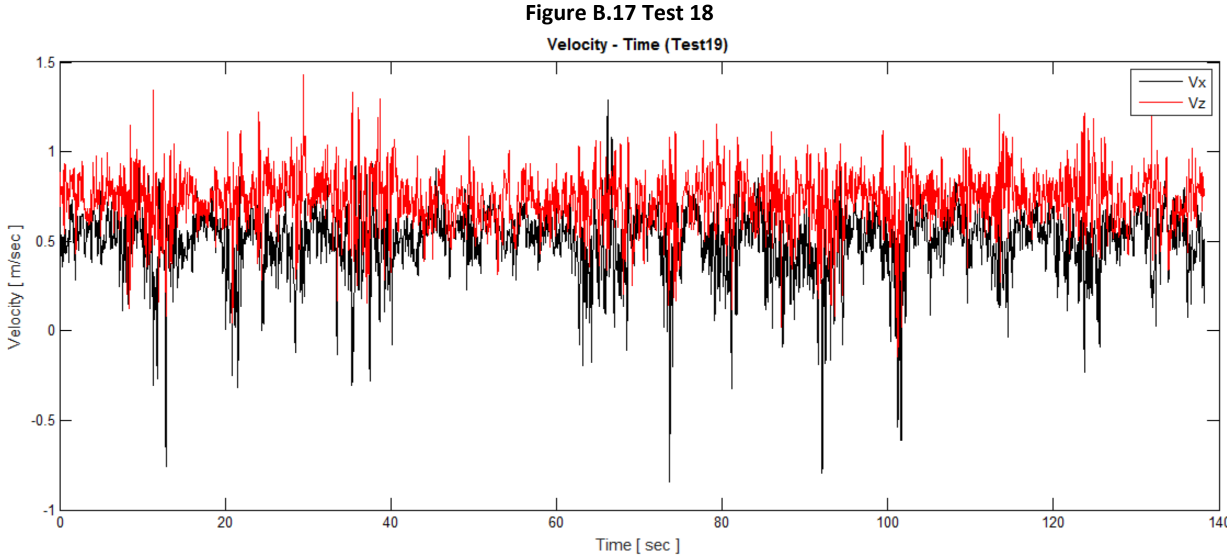

Figure B.18 Test 19

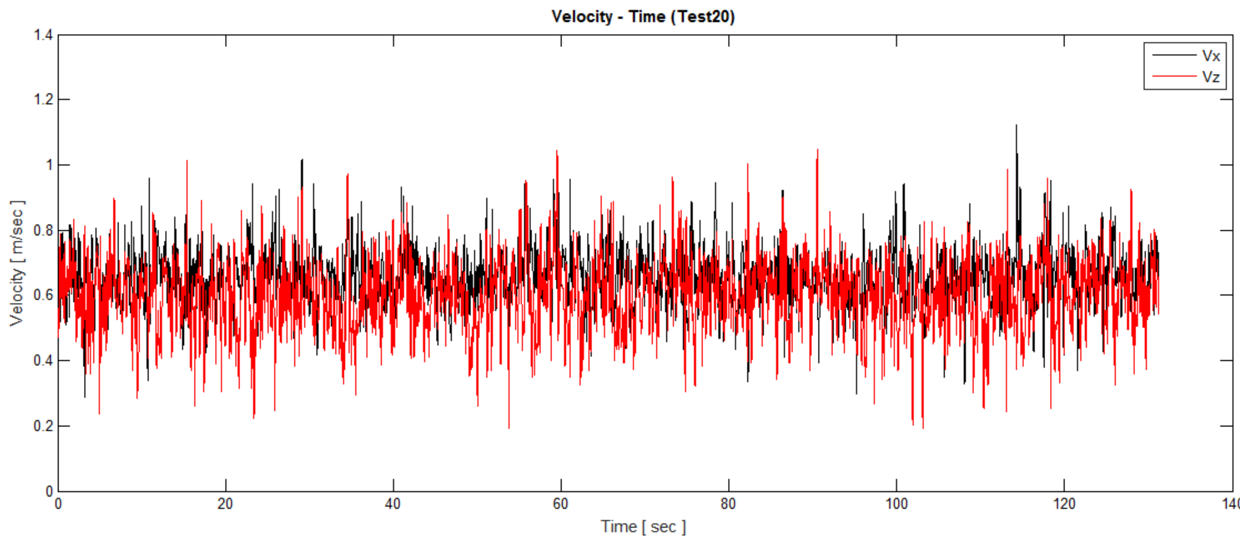

Figure B.19 Test 20

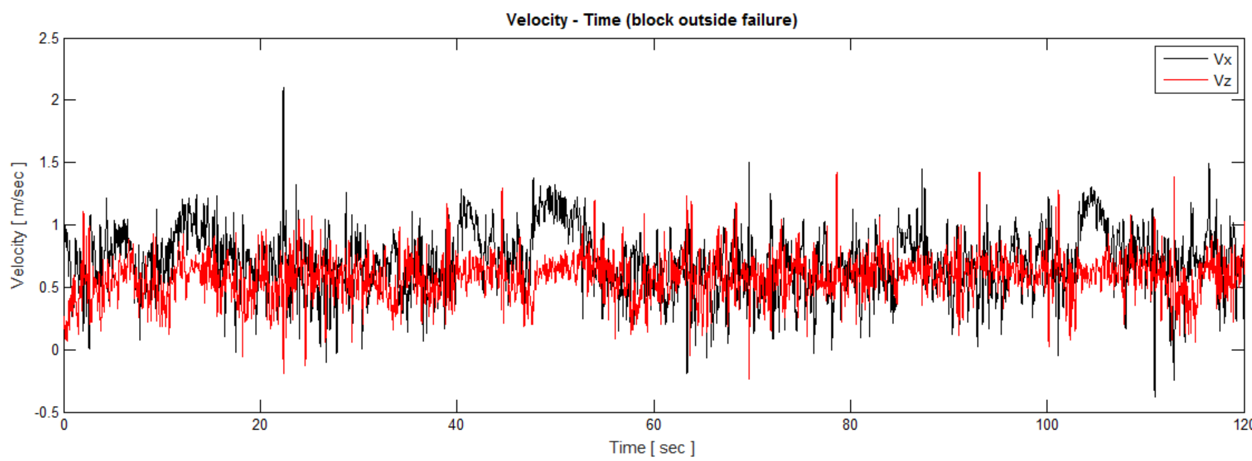

Figure B.20 Test 21

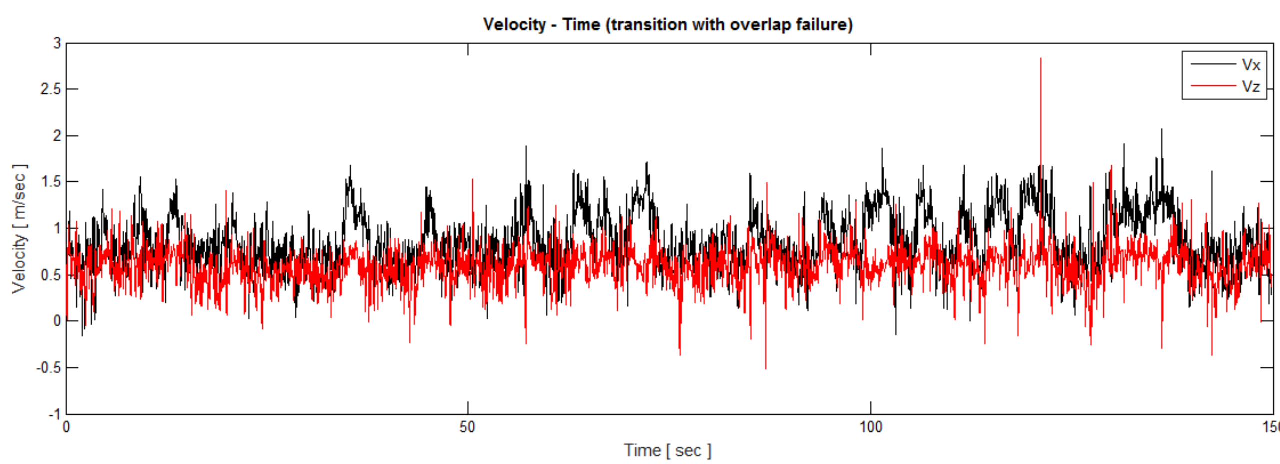

Figure B.21 Test 22

Appendix C - Script and tables with α values

The Matlab script for the calculation of α values is presented below:

```
close all;clear all;

u1=input('Enter u1 value');
xstd1=input('Enter xstd1 value');
zstd1=input('Enter zstd1 value');
ystd1=xstd1/1.9;
k1=(1/2)*(xstd1^2+ystd1^2+zstd1^2);

u2=input('Enter u2 value');
xstd2=input('Enter xstd2 value');
zstd2=input('Enter zstd2 value');
ystd2=xstd2/1.9;
k2=(1/2)*(xstd2^2+ystd2^2+zstd2^2);

syms a
eqn=(u1+a*sqrt(k1))^2==(u2+a*sqrt(k2))^2;
solve(eqn,a)
```

In the following tables the values of α for the different 'combinations' of tests (C.1: last row of blocks and C.2: middle blocks) are presented:

α - values	Test 05	Test 06	Test 16	Test 19
Test 05				
Test 06	-5.9895 -2.5620			
Test 16	-7.8330 -2.3597	-8.3218 -2.3256		
Test 19	-2.3633 -2.6524	-2.6145 -2.2000	-0.9472 -2.3587	

Table C.1 α values (edge blocks failure)

α - values	Test 08	Test 11	Test 12	Test 14	Test 21
Test 08					
Test 11	4.1640 -4.5595				
Test 12	1.5496 -3.7762	0.1980 -3.1533			
Test 14	0.5852 -3.9171	-1.0451 -3.2959	-10.2577 -2.8436		
Test 21	0.7205 -3.9754	-1.0419 -3.3379	-122.7540 -2.8727	-1.0712 -3.0015	

Table C.2 α values (middle blocks failure)

Appendix D - Lab Photos

Figure D.1 1st Test Series_1

Figure D.2 1st Test Series_2

Figure D.3 2nd Test Series_1

Figure D.4 2nd Test Series_2

Figure D.5 2nd Test Series_3

Figure D.6 3rd Test Series

Figure D.7 EMS above the block mat