Channel Protection

Gabion Mattresses and Concrete Blocks

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Report SR 427
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Summary

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Prior to the present study, HR Wallingford was commissioned by the Department of the Environment to investigate the stability of riprap and loose concrete blocks for channel protection in highly turbulent flows. The results of that study are described in HR Report SR 313 (Escarameia and May, 1992). HR was later commissioned to carry out a follow-up project which can be divided in two parts: 1. field measurements of turbulence in rivers, and 2. laboratory tests of gabion mattresses and cabled concrete blocks. The first part of the study was presented in HR Report SR 424 (Escarameia et al, 1995) and the second part is the subject of the present report.

Tests were carried out with loose solid concrete blocks, scale models of 300mm thick Reno mattresses (1:5 scale), and cabled and interlocking blocks both at a scale of 1:8. The materials were placed on a flat bed and tested for a wide range of flow conditions, from normal river flow to very high levels of turbulence.

The results of the tests were analysed with the same procedures used in HR Report SR 313 for the analysis of riprap and loose blocks. Design equations incorporating a coefficient to account for the level of turbulence are recommended for protection schemes using Reno mattresses, loose blocks and cabled block mattresses. Reno mattresses were found to be considerably more stable than equivalent riprap: for example, under normal turbulence conditions the required size of the filling stone in a 300mm thick Reno mattress is approximately half the size of riprap needed under the same flow conditions. The study also showed that the level of tension imposed by the cables in block mat revetments does not appear to have a significant effect on their stability.

Notation

a,b	Size of mesh opening
C	Stability coefficient
D_n	Thickness of blocks or size of the equivalent cube
d_{50}	Dimension of stone below which 50% of the stones by weight are smaller
e	Voids ratio
F_r	Froude number
g	Acceleration due to gravity
K_h	Depth factor in Pilarczyk's equation (1990)
K_s	Slope factor in Pilarczyk's equation (1990)
K_T	Turbulence factor in Pilarczyk's equation (1990)
k_r	Coefficient in Pilarczyk's equation (1990)
l_1,l_2,l_3	Cell dimensions
n	Porosity
s	Specific gravity of revetment material
TI	Turbulence intensity $(TI = \frac{rms\ x'}{\bar{x}})$
U	Mean flow velocity over cross-section
U_d	Depth-averaged velocity
u	Streamwise velocity component
V_s	Volume of solids
V_v	Volume of voids
V_b	Mean velocity near the bed
v	Transverse velocity component
w	Vertical velocity component
y_o	Flow depth
α	Angle of bank to horizontal
Δ	Relative density of mattress
θ	Internal friction angle of stone
ρ_s	Density of mattress material
ρ_w	Density of water
ϕ	Stability factor in Pilarczyk's equation (1990)
ψ_{cr}	Critical shear stress parameter in Pilarczyk's equation (1990)
$\bar{x}$	Time-averaged value of quantity x
x'	Fluctuation around the mean value of quantity x

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1 Introduction

In the period of 1990 to 1992 an experimental study was carried out by HR Wallingford to investigate the stability of riprap and concrete blocks for channel protection in highly turbulent flows; the results are described in HR Report SR 313 (see Escarameia and May, 1992). Tests were carried out with various degrees of turbulence ranging from normal levels in uniform channels to very high levels downstream of hydraulic jumps. Based on the laboratory work, design equations were developed to size riprap and loose concrete blocks; these took quantitative account of the destabilizing effect of the flow turbulence, amongst other relevant parameters. The study had been partly funded by the Department of the Environment (DOE) who later commissioned a follow-up project with two objectives: 1. to collect field data on typical levels of turbulence in rivers for use in the design equations proposed in the first study (first part of the project); and 2. to extend the range of channel protection materials to gabion mattresses and cabled concrete blocks (second part). The first part of the project was described in HR Report SR 424 (see Escarameia and May, 1995). The present report deals with the laboratory tests carried out on gabion mattresses and concrete blocks and can be considered as an extension of HR Report SR 313, 1992. The tests with gabion mattresses were supported by Maccaferri S.P.A.

The above mentioned HR Report SR 313 gives some general backgound information on turbulence and on the initiation of particle movement. It also includes an extensive literature review of design formulae for riprap and concrete blocks as channel protection materials. Particular attention was given to investigating their suitability as revetments downstream of hydraulic structures where flow turbulence plays an important role. The literature search showed that the existing guidelines do not apply satisfactorily to highly turbulent flows and that the various design equations give widely varying sizes for riprap. It also showed that very little independent work had been carried out to quantify the performance of revetments consisting of concrete blocks (either loose or cabled).

The method for analysing the results of the present study closely followed the procedures adopted in the earlier study. Rather than developing new equations for the sizing of gabion mattresses and cabled concrete blocks, the data were used to determine adequate stability coefficients for each type of channel protection.

Section 2 of this report gives a description of the materials tested and summarizes the available information in the existing literature. The experimental set-up and instrumentation used in the tests are presented in Section 3, and some background information used in the analysis of the data is given in Section 4. Section 5 presents the test results and Section 6 deals with the data analysis. The conclusions and recommendations from the study are given in Section 7.

2 Materials tested

2.1 General considerations

Two types of channel revetment were selected for investigation under the present study: gabion mattresses and cabled concrete blocks. Both types have some common characteristics which make them suitable for controlling erosion in rivers and channels. Because of their flexibility and mattress-like shape, both materials allow coverage of banks and river beds with relative ease and economy of installation; provided that a regulating layer is laid as a base for the mattress, the contour of the channel can be followed smoothly, resulting in a continuous revetment with uniform thickness. Adequate fixing of the mattresses at the ends and installation of filter layers are considered to be of paramount importance to ensure a good performance of the revetment.

2.2 Gabion mattresses

Gabion mattresses are essentially rock-filled wire mesh boxes which have a large surface area compared to their thickness. They retain the advantages of riprap in that they constitute a flexible, permeable revetment. In addition to that, the flexibility of the mesh boxes allows them to deform when subjected to current or wave forces without failing, while the rockfill inside the boxes is contained by the mesh. Failure of a revetment can be defined as a situation where erosion of the underlying material occurs. In the specific case of gabion mattresses this is likely to happen when the movement of the filling stone inside the mesh box is such that the stone depth is reduced to the medium size of the rock. For the present tests, failure conditions were defined as corresponding to incipient movement of the stone inside the boxes.

In river engineering the use of gabion mattresses can be found in a number of situations which include, for example, river bed and bank protection against erosion caused by current and wave attack, and local protection against scour around bridge piers and downstream of weirs, gates and culverts. For the present study it was decided to investigate the stability of a proprietary brand of gabion mattresses which has a large record of applications worldwide, including the UK. The revetment chosen is called Reno mattress and is manufactured by Officini Maccaferri S.p.A., Italy. These mattresses are manufactured with a hexagonal, double twisted mesh made of zinc coated mild steel wire; in corrosive environments the wire can be coated with PVC to increase its resistance to chemical attack. Each mattress unit is divided into several cells which have the purpose of restricting the movement of the stone fill within a smaller area and thus increasing the overall strength of the mattress. On site the individual cells are usually assembled together, then the mattresses are placed in position and wired with adjacent mattresses before they are filled with stone; once the stone is placed in the wire boxes the lids of the mattresses are positioned on top and also wired down. When the mattresses are laid underwater they are assembled before positioning.

2.2.1 Existing information

Several research organizations have in the past been commissioned by Maccaferri to carry out research on the stability of Reno mattresses. These studies have concentrated on assessing their performance under wave and current attack but information is lacking on stability in highly turbulent flow conditions.

One of the most comprehensive of these studies was carried out by Simons et al (1984) at the Engineering Research Center of the Colorado State University, USA. The main objectives of the study were: 1. to measure the hydraulic roughness of the Reno mattresses; 2. to assess requirements of granular and synthetic filter layers; and 3. to develop suitable design criteria for stability of the mattresses under various current flow conditions. Both model scale and full-size tests were conducted in this study.

In the 1:3 scale tests a commercial mesh was used to reproduce the mattress boxes but dynamic similarity was not achieved, resulting in a relatively greater flexibility. The study involved the testing of mattresses of various thicknesses and values of the critical velocity were determined. This is defined as the velocity of the flow at which the stones inside the mattresses begin to move in the main direction of the flow. For mattresses corresponding in the prototype to 300mm thickness, the critical velocities obtained were 4.97m/s (for Froude number smaller than 1.5) and 4.18m/s (for Froude number greater than 3). As the flow velocity increased, a considerable number of stones would move inside the mattress cells from the upstream to the downstream part of the cell. This mass of rock would eventually cause the mesh to deform and rippling of the surface would occur. It was found that if the reduced depth of rock at the upstream end of the mattress cells was bigger than the median size of the stone, the underlying layer would not be eroded. The flow velocity for this situation was called the limiting velocity. In the Colorado tests the maximum velocity achieved corresponded to about 6m/s, but even at this velocity failure of the mattresses was not observed.

The full-size tests used 150 and 225mm thick mattresses and were carried out in a flume with a slope of 13%. Considerable difficulties in the measurement of the flow depth were, however, encountered due to the turbulence generated by the high speed flow over the steeply laid mattresses.

Other conclusions from the Colorado study, besides the critical velocities mentioned, were: 1. the incipient motion of the filling stone in the mattresses occurs at about 1.4 times the flow velocity and twice the shear stress that cause incipient motion for loose rock of the same size; 2. the mattress stability depends to a large extent on the cell lengths; 3. the mesh has an insignificant effect on the mattress roughness.

More generally, Pilarczyk (1990) presented an equation for design of riprap and mattresses used in channel protection. This equation features a number of different coefficients, amongst which one that takes qualitative account of the turbulence level of the flow. Using the coefficients appropriate for mattresses, Pilarczyk's equation is applicable to both concrete and gabion mattresses and can be written as follows:

$$D_n = (\phi / \Delta) (0.035 / \psi_{cr}) K_T K_h K_s^{-1} (U_d^2 / 2g) \qquad (1)$$

where:

D_n is the average thickness of the mattress;

ϕ is a stability factor
1.0 for exposed edges of mattresses
0.5 for continuous protection;

Δ is the relative density of the mattress
$\Delta = (1-n) (\rho_s - \rho_w) / \rho_w$
ρ_s and ρ_w are the density of the mattress material and of the fluid, respectively;
n is the porosity;

ψ_{cr} is the critical shear stress parameter (= 0.06 - 0.10 for mattresses);

K_T is the turbulence factor

2/3 for low turbulence, uniform flow

1.0 for normal turbulence in rivers

2.0 for high turbulence, local disturbances and outer bends of rivers. This value should only be used when the velocity used in the equation is the average velocity for the whole cross-section (U), instead of the local depth averaged velocity (U_d);

K_h is the depth factor

$K_h = 2 / (\log (12y_0 / k_r))^2$ for logarithmic velocity profile

$k_r = D_n$ for concrete blocks

$k_r = 2D_n$ for rock;

$K_h = (y_0 / D_n)^{-0.2}$ for partially developed velocity profile;

y_o = flow depth

K_s is the slope factor

$K_s = (1 - (\sin^2\alpha / \sin^2\theta))^{0.5}$

where α is the angle of the bank to the horizontal and θ is the internal friction angle of the stone;

U_d is the depth-averaged flow velocity;

g is the acceleration due to gravity.

As can be seen, this equation requires an estimate of the state of development of the flow (whether it is partially or fully developed) and there is also some uncertainty regarding the appropriate value of k_r to use for gabion mattresses. However, this is still the most comprehensive equation for design of mattresses identified during this study.

2.2.2 Description of mattresses tested

Contacts were established with Maccaferri, and more precisely, with one of their UK agents, River and Sea Gabions Ltd, to choose the type of Reno mattress to test in the laboratory and decide on the necessary model scale. Since the range of flow conditions covered by the tests would span from normal river flow to very high levels of turbulence, it was decided to simulate 0.300m thick mattresses which are amongst the thickest mattresses manufactured by Maccaferri. Considerations regarding the maximum flows and velocities that could be achieved in the test rig led to the adoption of a model scale of 1:5. The required sizes of the mattresses, wire mesh and filling stone were then determined.

The scaled mesh boxes were fabricated by Maccaferri in Italy. The test section in the laboratory flume required two mattresses of the following dimensions: 1m x 1m x 0.06m (length, width and thickness); and one slightly shorter, only 0.80m long. Although the test section was 1.2m wide, the scaled mattresses only measured approximately 1m in width to facilitate their positioning in the flume. The 0.2m gap was set to one side of the channel and filled with purpose made mattress units after the main units were placed in position. Each mattress was divided into ten cells 0.50m (l_1) by 0.20m (l_2) in plan with their bigger dimension transverse to the direction of the flow. The model dimensions of the mesh, a and b, were 19 and 20mm, respectively. A sketch of the mesh boxes used in the tests is presented in Figure 1.

According to Maccaferri's literature and to specific advice received for this project, the stone filling for a 0.300m Reno mattress is normally in the range 100 to 150mm. In terms of d_{50} (the size of stone below which 50% of the stones by weight are smaller), it will typically be around 0.125m. At a scale of 1:5 the model stone would need to have a value of d_{50} of 25mm and be fairly narrow-graded so that the smaller sizes would be contained within the mesh. However, some difficulties were encountered before a suitable stone was found for the tests. A first batch of stone was rejected on the basis that its d_{50} was substantially below the required one; its granulometric curve also showed too wide a range of stone sizes. The second batch ordered was also checked by HR's Sedimentation Laboratory and revealed a value of d_{50} of 23mm which, in prototype terms, corresponds to 0.115m. The specific weight of the stone was determined and found to be equal to 2680 kg/m^3. This batch of stone, which was angular in shape, was considered adequate and was therefore used to fill the mattress boxes. The granulometric curve obtained is shown in Figure 2 and the characteristics of the mattresses are summarized in Table 1.

The operation of filling the mesh boxes followed closely the instructions provided by Maccaferri as it was important to reproduce the mattresses and wiring operations as accurately as possible. It was soon realized that they had to be assembled outside the flume and then positioned in the test section because the lacing was a very time consuming and delicate operation. Since the mattresses could not be allowed to deform during their positioning in the flume, strong steel base plates had to be made to enable each mattress to be lifted on a flat base. Each of the three Reno mattresses was therefore filled with stone outside the flume, well compacted and covered with the lids. These were tighly fixed with continuous lacing wire at the perimeter of the mattresses and at all the transversal diaphragms. As requested by Maccaferri, a "quilt " effect was obtained, with the centres of the cells having a greater thickness than the borders. The lacing wire adopted was flexible tinned copper wire similar in diameter to that used for the mesh (approximately 0.4mm) - see Plate 1. Once in the flume, the three mattresses and the sections placed on the side gap were also laced together as shown in Plate 2.

Cement mortar was poured into the upstream and downstream cells to prevent lifting of the mattresses at the ends. In order to facilitate the observation of stone movement within a cell, red paint was sprayed on the upstream half of each cell to form bands transverse to the flow (see Plate 3). At incipient movement conditions, red painted stones would be seen to travel along the cell to the non-painted area.

While the mattresses were being assembled and filled, the rock that was placed in each cell was carefully weighed and the cell dimensions were recorded. This allowed the calculation of the voids ratio, e, which is defined as follows:

$$e = V_v / V_s \qquad (2)$$

where V_s is the volume of solids (ie weight of stone divided by its specific gravity) and V_v is the volume of voids (defined as the difference between the volume of the cell and the volume of solids). The average value of the voids ratio was found to be 0.65. In general terms the bigger the stone size the smaller the voids ratio is likely to be. Bearing this in mind and the fact that the average stone size was 23mm, the value found for e is somewhat lower than that determined for riprap in the previous study (for example, a voids ratio of 1.0 was obtained for stone size 9.3mm, see Escarameia and May, 1992). This indicates a relatively high compaction which, according to Maccaferri, should also be achieved on site applications.

2.3 Blocks

Most of the tests involved cabled and interlocking blocks but some preliminary tests were carried out with scale models of loose concrete blocks. These loose blocks, which were specifically made for the study described in Escarameia and May (1992), were solid and made of a cement mortar having a specific weight of 2330kg/m^3; their dimensions were 0.030m (length) x 0.030m (width) x 0.008m (thickness). The loose blocks were re-tested in order to check conformity between the present study and the earlier one.

The main tests were carried out with models of cabled and of interlocking blocks. These were 1:8 scale models of the proprietary brand Armorflex 140 and Armorloc which are manufactured by MMG Civil Engineering Systems Ltd. The models used in the tests were existing blocks kindly loaned by Dr. R. Baker of Salford University. They had been carefully made for a previous research study with a specific gravity similar to that of concrete. The outside dimensions of the Armorflex models were 0.040m (length) x 0.036m (width) x 0.013m (thickness) and those of the Armorloc models were 0.049m (length) x 0.037m (width) x 0.011m (thickness).

The Armorflex block mat consists of rectangular concrete blocks with vertical holes; the blocks are tied together by means of horizontal cables that run through two cable ducts in each block. An interlocking effect is also achieved since the blocks are cabled together in a staggered fashion (see Figure 3). The blocks are slightly tapered inwards from near the bottom to the top, with the objective of allowing better articulation of the mattress. The Armorflex mattresses are supplied with the standard dimensions of 6m x 2.4m and are usually installed with a synthetic filter layer underneath. A granular layer can also be placed over the mattresses which, apart from the environmental benefits of vegetation growth, is claimed to increase their resistance to wave attack. In many cases the mattresses are blinded with gravel to enhance friction between the blocks. The shape of the Armorflex blocks as they are produced nowadays differs somewhat from that of the models tested; they are now slightly more rounded. However, this small difference is unlikely to account for major changes in the stability of the blocks.

The Armorloc mats are formed by blocks that interlock with a dovetail configuration and are suited to areas where hand installation is required due to lack of sufficient space for machinery to operate. They are also used when the area to be protected is small, such as near culverts, drainage channels, etc. The blocks have two vertical holes and a double taper which allows free articulation in both the longitudinal and the transverse planes (see Figure 3). As in the case of the Armorflex mats, a synthetic filter layer is usually placed beneath the blocks, and blinding of the joints is normally carried out with fine granular material.

3 Experimental set-up

3.1 Test rig

The general layout of the test rig is shown in Figure 4. As can be seen in the figure, a 28m long by 2.4m wide flume fitted with three pumps was used for the tests. The maximum flow achievable in the rig is 0.4 m^3/s and tailwater depths are controlled by means of a flap gate at the downstream end of the channel. The width of the flume was reduced from 2.4m to 1.2m to enable a wider range of velocities and flow depths. This was achieved by installing a partition wall which divided the flume into two parallel channels one of which was blocked by a bulkhead. A smooth concrete weir with an ogee crest profile was designed and built in the test channel with the objective of creating a large enough pressure head that would produce high velocities at the base of the weir. By lifting the tailwater gate, a hydraulic jump could be formed which would generate the higher levels of turbulence required for the tests. Depending on the water levels dowstream, the weir would also create a head of water sufficiently large to produce supercritical flow in the test section so that the stability of the gabion mattresses and concrete blocks could be studied in rapid flow conditions.

The model materials were placed in a flat 2.8m long test section, 2.5m downstream of the concrete weir; the transition between the smooth surface of the weir and the model materials was achieved by a fixed rough bed. This consisted of gravel (approximately 5mm in size) which was cemented to the surface of the concrete slab that formed the bed of the channel. A 0.15m high end sill was built downstream of the test section in order to fix the hydraulic jump within the length of the test section. Holes were cut at the two extremities of the sill to facilitate drainage of the test section.

Different arrangements were required for testing the gabion mattresses and the concrete blocks due to the different thicknesses and weights of the two types of model material. For reasons that were explained in Section 2, the model gabion mattresses had to be assembled outside the test rig, on strong steel plates which were then lifted into the flume by means of an overhead gantry. Once in the flume, the steel plates with the model gabions sat flat on the bed with their top flush with the level of the upstream fixed bed. Since the concrete blocks tested were of smaller thickness than the model gabions, it was necessary to place the blocks on a false wooden floor to ensure that the blocks were, as the gabions, flush with the upstream fixed bed.

3.2 Instrumentation

The test rig is equipped with a Crump weir and accurate water level gauge for measurement of the flow discharge at the downstream end of the flume. A calibration of this weir was carried out before the start of the tests. Checks using a miniature current meter to measure the mean flow velocity in conjunction with measurements of the water depth in the test section were done regularly to assess the performance of the Crump weir. The flow depths in the test section were determined by scales fixed to the transparent sections of the walls of the flume.

Values of instantaneous flow velocity were measured by a two-component electromagnetic current meter (Columbrock EMCM). The EMCM has a 32mm discus head and can be positioned in either a vertical or a horizontal plane to suit the type of test being carried out, as will be described later in item 3.3. In the two possible positions the instrument measured the flow velocity in two orthogonal directions: these were the streamwise and the transverse directions when the head was in the horizontal plane, and the streamwise and the vertical directions when the head was in the vertical plane. With a sampling frequency of 125Hz, the EMCM also contains a filter which has a 3dB cut-off at 20Hz and a flat reponse characteristic to 2Hz. Before the beginning of the tests, the two channels of the electromagnetic probe were calibrated in HR's Meter Rating Tank. In addition to this, during the test programme several checks of the mean streamwise velocity were carried out using a miniature current meter. Previous experience with this type of electromagnetic probe indicated that, due to the sensitivity of the instrument to changes in temperature, regular monitoring of the offset signals at zero flow velocity was required. Therefore, the probe's offsets were recorded at the beginning and end of each test.

The point velocity measurements from the two-component probe were converted into mean and fluctuating velocities by a Mean Voltage Meter and an RMS (root mean square) Meter with two channels each. The rms values were determined by the difference between the instantaneous signal from the probe and the value given by the Mean Voltage Meter. Both values were read directly from the meters' displays.

3.3 Test procedure

Two types of flow condition were considered in this study: normal channel flow, and flow with higher levels of turbulence which were produced by a hydraulic jump at the base of the weir. In the normal turbulence tests the tailwater gate was kept fully open, so that the downstream water levels were sufficiently low to avoid formation of a hydraulic jump, and the flow rate was gradually increased to cause initiation of particle movement.

It was soon realized that very rapid flow conditions needed to be achieved if any movement was to be observed in the tests of the gabion mattresses and later on during the tests of cabled blocks. In these situations the discus of the probe was positioned in a horizontal plane since the small depth of the flow would not otherwise allow measurements to be taken at the required level (see Section 4). At the beginning of each high turbulence test the tailgate was set quite high and was then gradually lowered until movement of the test materials was observed. In these tests the probe was positioned such that the plane of the discus was vertical and, as in the other type of test, at about 1m downstream of the end of the fixed bed section.

4 Background information

4.1 General

Detailed information on turbulence in flows and on initiation of particle movement was presented in the report that described the previous study of channel protection revetments (see Escarameia and May, 1992). That report also included an extensive literature review of existing formulae for the design of riprap and concrete blocks under current attack. This Section will therefore concentrate on presenting and defining the most relevant concepts and parameters used in the analysis of the present test results.

4.2 Turbulence

When the levels of turbulence in the flow are high the movement of the fluid particles is very erratic causing rapid and sometimes large changes in the velocity direction and intensity. It is generally accepted to consider the instantaneous velocity vector V as the sum of two terms: the mean, $\bar{V}$, and the turbulent fluctuations around the mean, V'. This can be expressed as follows:

$$V = \bar{V} + V' \qquad (3)$$

In very turbulent flows the erratic nature of the flow paths can cause the instantaneous velocity components, u, v and w in the three orthogonal directions (streamwise, transverse and vertical, respectively) to be of the same order of magnitude.

The importance of the turbulent fluctuations in relation to the time-averaged mean can be assessed by a parameter called the turbulence intensity which is defined as follows for the three velocity components:

$$TI_u = (\overline{u'^2})^{1/2}/\bar{u} \qquad (4)$$

$$TI_v = \overline{(v'^2)}^{1/2}/\bar{u} \quad (5)$$

$$TI_w = \overline{(w'^2)}^{1/2}/\bar{u} \quad (6)$$

The numerators are commonly known as the rms values (root mean square values) and correspond to the standard deviation from the mean.

4.3 HR's design equations

The earlier study recommended design equations for the stability of riprap and of concrete blocks in flows with various levels of turbulence. In the analysis then carried out a turbulence coefficient was defined in terms of the turbulence intensity in the streamwise direction, TI_u. The electromagnetic current meter used in the present study allowed velocity readings to be taken not only in the streamwise direction but also in the transverse or vertical direction, depending on the way the probe was positioned in the flume. Although not essential for the analysis, the additional data on the non-streamwise components was collected and considered as an important indication of the flow conditions.

It was found that the stability of channel revetments depends strongly on the value of the near-bottom velocity V_b and on the turbulence intensity at the same level. A reference level corresponding to 10% of the water depth above the bed was adopted for the following reasons: 1. it is sufficiently close to the bed to be representative of flow conditions experienced by the revetment; 2. it is less affected by errors involving the vertical positioning of the velocity measuring instrument than levels closer to the bed where the velocity gradient is steeper; and 3. it is suitable for measurements in physical models and on site.

The design equations developed from the previous study were of the form:

$$D_n = C\ (1/(s-1))\ (V^2_b / 2g) \quad (7)$$

where:
D_n is the size of the equivalent cube (for stone) or the thickness of the blocks;

C is a stability coefficient that varies with turbulence;

s is the ratio of the density of the revetment material to the density of the water; and

g is the acceleration due to gravity.

For safe design of riprap on a flat bed and bank slopes of 1V:2H or flatter the coefficient C recommended was:

$$C = 12.3\ TI - 0.20 \quad (8)$$

where :

$TI = TI_u$ = rms u / V_b at 10% of water depth above the bed
and $TI \geq 5\%$. If, for example, the turbulence intensity is 10%, TI should be entered in equation (8) as 0.10.

For safe design of loose concrete bloks on gradients flatter than 1V:2.5H the coefficient C recommended was:

$$C = 0.75\ (12.3\ T1 - 0.20) \qquad (9)$$

For riprap, the size of the equivalent cube, D_n,is related to the D_{50} value of the stone by: D_n=0.90D_{50} (see Escarameia and May, 1992).

5 Tests

5.1 General

In the tests the velocity readings were taken at approximately 10% of the water depth above the bed so that the measurements could be analysed in the same way as the results of the previous study. The results are presented in Tables 2 to 10. Readings of the local mean velocity in two orthogonal directions were obtained as well as the rms values of the velocity fluctuations. As mentioned in Section 3, in the high turbulence tests the two orthogonal velocity components recorded were the streamwise and the vertical components; in the rapid flow tests they were the streamwise and the transverse components. Shown in the tables are also the turbulence intensities at 10% of the water depth, TI_u and TI_v (or TI_w), which were calculated with equations (4) to (6).

The flow depth, y_0, and the mean cross-sectional velocity, U (calculated from the ratio of flow discharge to the cross-sectional area of the flow) are also presented in the tables. The right hand column of the tables contains observations regarding the state of motion of the materials tested. In the tests where some movement or collapse occurred the value of the Froude number is also presented and was calculated as follows:

$$F_r = U / (g\ y_0)^{0.5} \qquad (10)$$

where g is the acceleration due to gravity.

5.2 Reno mattresses

The results of tests with Reno mattresses under high turbulence and rapid flow conditions are presented in Tables 2 and 3, respectively. It can be seen that the failure of the mattresses was never reached in spite of using the full flow capacity of the test rig. Furthermore, it was not possible to achieve conditions for which the mattress mesh was deformed by the movement of the rock filling inside the cells. The velocity associated with this condition is called the limit velocity. Rocking or small translatory movements of stones inside the cells were, however, observed; the mean flow velocity corresponding to this latter situation is called the critical velocity. Plate 4 was taken at the end of one of such tests and shows the movement of some stones inside the mattress cells.

5.3 Loose concrete blocks

The loose blocks were laid by hand in a staggered pattern on the bed of the flume to form a continuous mattress. Sand with a d_{50} size of 0.7mm was spread over the mattress to fill any gaps between the blocks.

Table 4 shows the results of the tests, all of which were carried out under high turbulence conditions. Total collapse of the revetment was reached in test CL8. It was, as expected, very sudden since the movement of one block caused the rapid and progressive movement of the others. This type of failure had already been observed in previous tests with loose blocks.

5.4 Cabled blocks

It was decided to test the cabled blocks with three qualitative levels of tension: level A, where the cables were tightly stretched; level B, where the cables were stretched but to a lesser extent; and a third level where no tension was applied to the cables although the blocks were tied together. This latter level, which corresponds to no tension, is more likely to represent prototype conditions for Armorflex and Armorloc installations as cable tension is not expected to last long, according to the manufacturer. Furthermore, the relative size of the cables and cable-ducts is such that blocks can move before being restrained by the cables and this would be considered as failure. A metal frame surrounding the blocks was made to allow application of the required tension to the block mattress. This frame consisted of two thin plates to which the ends of the cables were fixed, and two threaded rods that could be adjusted to give the necessary tension (see Plate 5).

Most of the tests were carried out with the block mattress positioned such that the cables were normal to the main flow direction; the effect of the orientation of the blocks was investigated by carrying out some tests with the cables in the flow direction. In all tests, sand with d_{50} equal to 0.7mm was spread over the mattress in order to fill the vertical holes of the blocks and the gaps between adjacent blocks. An increased granular interlocking effect might be achieved with slightly bigger grain size. As a result of previous experience, it was decided not to use any type of filter layer beneath the mattress. The previous study of channel revetments had shown that in highly turbulent environments the presence of a granular filter layer can actually destabilise the revetment; tests using a geotextile had also shown that the stability was no higher than achieved without a filter layer. However, the manufacturers of the Armorflex and Armorloc mattresses recommend the use of a geosynthetic fabric underneath the blocks to prevent migration of fine particles through the holes in the blocks.

The results of the tests with cabled concrete blocks are summarised in Tables 6 to 9. With level of tension A, it can be seen that no movement was registered in the high turbulence tests and that only movement of the upstream row was observed in the rapid flow tests (Tables 6 and 8). Small lifting movements occurred in the mid section of the mattress during tests with rapid flow when the tension of the cables was at level B (see Table 8, test CRB2). Total collpase of the revetment was observed when the blocks were tied together but not tensioned, as can be seen in Table 9, test CH2.

5.5 Interlocking blocks

For the testing of the interlocking blocks it was decided to apply some constraint to the movement of the blocks at the upstream and downstream ends of the mattress in order to better simulate prototype conditions. This was carried out by placing wooden battens transversely to the direction of the flow at the two ends of the mat. No constraint was provided at the sides of the mattress. As in the other tests with concrete blocks, 0.7mm sand was used to fill the holes and gaps of the mattress.

The results of the two high turbulence tests, are presented in Table 10 where it can be seen that the collapse was reached in test IB2. This collapse was, as expected, quite sudden and caused total loss of the blocks as they were washed away by the flow.

6 Data analysis

6.1 Model-prototype conversion

The tests of Reno mattresses and cabled or interlocking blocks were carried out with scale models of these materials. As mentioned in Section 2, the geometric scales were 1:5 for the Reno mattresses and 1:8 for the blocks. In order to convert model values into their corresponding prototype values, it is necessary to adopt a suitable similarity law. Since forces due to gravity and inertia are dominant factors in open-channel flows, it is appropriate to adopt the Froudian similarity law. According to this law the model values should be multiplied by the following conversion factors to give the prototype values:

Geometric scale	1:8	1:5
Length, width, water depth	8	5
Velocity	$8^{0.5} = 2.828$	$5^{0.5} = 2.236$
Flow discharge	$8^{2.5} = 181.0$	$5^{2.5} = 55.90$
Turbulence intensity	1	1

6.2 Analysis of tests with Reno mattresses

The mean and near-bed flow velocities in tests where stone movement was observed were converted into prototype values using the relevant factor presented in Section 6.1 (see Table 11). Values of the coefficient C were then determined from Equation (7), and plotted in Figure 5 against the turbulence intensity in the streamwise direction which from now onwards will be simply called TI. Since Reno mattresses are essentially riprap with extra strength provided by the wire mesh, data that had been obtained for riprap in the previous study are also shown in the figure to allow comparisons. It can be seen that the Reno mattresses tested are considerably more stable than riprap of equivalent size (note that all the experimental points corresponding to the Reno mattresses are to the right of equivalent riprap points). It is also noticeable in Figure 5 that in tests carried out with "normal" turbulence, movement of the stone inside the mattresses occured at much higher turbulence intensities (above 15%) than had been observed for riprap. This is likely to be due to relatively smaller ratios of water depth to stone size.

When compared with tests using riprap, the normal turbulence results with Reno mattresses indicate that for similar flow conditions the stable size of stone in the mattresses is approximately half that of loose riprap (compare C=0.36 for riprap with C=0.17 for Reno mattresses). This is in good agreement with the results of the Colorado study (see Simons et al, 1984) where it was found that the Shields coefficient for Reno mattresses is approximately double that of equivalent loose stone.

Although there is some scatter in the results, a good fit to the higher turbulence data was obtained with a linear equation having a gradient similar to that determined for riprap:

$$C = 12.3\,TI - 2.17 \qquad (11)$$

for $19\% < TI \leq 35\%$

Under normal turbulence conditions, C can be given by
C = 0.17
for TI≤19% (12)

For safe design it is recommended to adopt for the definition of C the envelope curve represented by the dashed line in Figure 5, which was drawn to include all the experimental points:

$$C = 12.3\ TI - 1.65 \quad (13)$$

for TI ≥ 15%.

A comparison can also be made between the mean flow velocities measured in the present rapid flow tests and those obtained in the Colorado study which caused initiation of stone movement in 300mm thick Reno mattresses (critical velocity)- see Section 2 and Simons et al, 1984. The mattresses were found to be stable up to mean flow velocities of 4.85 to 5.61m/s in the present study whereas in the Colorado study the critical velocity reached 4.18m/s for Froude numbers bigger than 3.0 or 4.97m/s for Froude numbers smaller than 1.5. In the present study the Froude number was of the order of 2.3 which suggests a greater stability compared with the 1984 study.

The present tests demonstrate that in highly turbulent flows stone movement does occur under mean cross-sectional velocities which are much lower than those mentioned above. This is shown in Table 2 (tests RH12 to RH15) where mean flow velocities of the order of 1.6m/s (prototype value) associated with turbulence intensities of around 30% were sufficient to cause stone movement.

6.3 Analysis of tests with loose concrete blocks

It can be seen in Table 4 that collapse of the mattress formed by loose concrete blocks was reached during Test CL8. The value of coefficient C given by equation (9) was calculated for this test and plotted in Figure 6 against the measured value of turbulence intensity, TI. Also plotted in the figure are the results of the tests carried out in the previous study. It is apparent that the new test value is consistent with the previous results and that all the tests can be conservatively described by the following design equation which was recommended in Escarameia and May (1992):

$$D_n = C\ (1/(s-1))\ (V^2_b / 2g) \quad (14)$$

with

$$C = 0.75\ (12.3\ TI - 0.20) \quad (15)$$

for TI ≥ 5%.

6.4 Analysis of tests with cabled blocks

The results of tests with cabled blocks indicated that collapse was more easily reached under rapid flow conditions than under highly turbulent flows, where the turbulence is high but the mean and local flow velocities can be relatively low. This applies to the three different levels of tension imposed on the blocks: tests with high levels of turbulence did not produce collapse of the mattresses but this situation was reached in several tests with very fast flow. It should be noted that in all the cases "collapse" only involved movement of the front row of blocks or intermittent lifting of blocks in the central region of the mattresses (and this case only for the medium level of tension, level B). The positioning of the cables in relation to the direction of the flow does not seem to have a strong effect on the stability of the revetment; however, tests CRA2 and CRA5 point to a slightly higher stability when the cable direction is transverse to the main flow direction (see Table 6).

Table 12 presents model and prototype velocity values for tests where movement occurred, as well as the corresponding values of the Froude number. The value of coefficient C was calculated for these tests and plotted in Figure 6 against the turbulence intensity TI (the result of test CH2 was not plotted because the value of TI was not available); in this figure the letter L was used to identify the tests where leading edge failure occurred as oposed to movement of blocks at mid sections of the block panel. Also plotted are points corresponding to tests carried out at high turbulence levels although collapse was not reached (these tests are identified by the letter N). In the determination of the values of C, D_n was taken as the ratio of the weight per unit area and the density of the model block material . A sample consisting of several model blocks was weighed and the average volume of the blocks was determined in order to obtain the density of the block material. This was found to be 2750kg/m^3. For the calculation of the weight per unit area, the area of the blocks was taken as that given by the outside plan dimensions (0.040m x 0.036m). This procedure led to the value of D_n equal to 0.0055m (model value) or 0.044m (prototype value) and is equivalent to porosity of n = 0.58, based on the overall dimensions of the blocks. In doing so, proper account is taken of the fact that the blocks were not solid but had instead an open shape. The same approach was followed for the analysis of the interlocking blocks, which had a density of 2700kg/m^3. The value of D_n determined was equal to 0.0050m (model value) or 0.040m (prototype value); this corresponds to a porosity of n = 0.55.

It can be seen in Figure 6 that, although failure was not reached in the high turbulence tests, it is still possible to define a relationship between C and TI that is safe compared with all the test data. Therefore, for high turbulence levels it is recommended to adopt the following equation for design of block mattresses (with tensioned cables):

$$C = 1.79\ TI - 0.72 \qquad (16)$$

For "normal" turbulence conditions, C can be taken as 0.05; the transition between this value and Equation (16) can be assumed to be at TI of about 43%, but there are no data in the range of TI between 12.5% and 52% to confirm this assumption. Given the above limitations, a value of C equal to 0.05 can be used up to turbulence levels of 43% and Equation (16) can be adopted for higher values.

6.5 Analysis of tests with interlocking blocks

The tests performed with interlocking blocks resulted in only one situation of collapse of the revetment (Test IB2 in Table 10); the mean and near-bed velocities reached during this test were converted into prototype values and are presented in Table 12. When plotted in Figure 6, the point corresponding to Test IB2 indicates, as expected, a greater stability for the interlocking blocks than for the loose concrete blocks also tested. However, because of the scarcity of the data, it is not possible to determine the relationship between the stability factor C and the turbulence intensity.

7 Conclusions and recommendations

7.1 General

An experimental study was carried out to investigate the stability of 300mm thick Reno mattresses and of cabled concrete block mattresses in environments with various levels of turbulence. The tests were performed with models of the revetments placed on a flat bed at scales of 1:5 for Reno mattresses and 1:8 for the concrete blocks. Additional tests were also carried out with loose solid concrete blocks and with interlocking blocks. The turbulence levels varied between normal turbulence, which corresponds to uniform flow in straight channels, to higher levels such as those occurring downstream of hydraulic structures.

7.2 Reno mattresses

1. The characteristics of the Reno mattresses tested are summarised in Table 1 and illustrated in Figure 1. They were tested at a scale of 1:5.

2. Failure of the Reno mattresses as a revetment, which corresponds to a situation where erosion of the underlying material occurs was not achieved in the tests, but incipient movement of stone within the mattress cells was observed. The mean flow velocity associated with this situation is called the critical velocity. During the test programme incipient movement was observed both in high-velocity, shallow flow tests where the turbulence levels were relatively low, and in high-turbulence conditions.

3. The stability of the Reno mattresses tested under both normal and higher turbulence conditions is considerably higher than that of riprap of equivalent size. For normal turbulence, the stable size of the stone filling in Reno mattresses is approximately half the size of loose riprap.

4. Under normal turbulence conditions the Reno mattresses tested were found to be stable up to mean flow velocities of 4.8 to 5.6m/s, with Froude numbers of the order of 2. This indicates a slightly higher stability than obtained in tests conducted by Simons et al (1984) who found the critical velocity to be 4.18m/s (for F_r>3.0) and 4.97m/s (for F_r<1.5).

5. Under highly turbulent flows stone movement within the mattresses occurs for mean cross-sectional velocities which are much lower than those observed under normal turbulence flows (values of the order of 1.6m/s were observed compared with velocities of around 5m/s for normal turbulence). This finding highlights the importance of taking account of the turbulence level in design.

6. The following best-fit equation was found for the stability of 300mm thick Reno mattresses on a flat bed:

$$D_n = C \frac{1}{s-1} \frac{V_b^2}{2g} \qquad (17)$$

where

C = 0.17	for	T1 ≤ 0.19 (ie 19%)
C = 12.3 TI-2.17	for	0.19 < T1 ≤ 0.35

For safe design it is recommended to adopt for the definition of C the envelope curve shown by a dashed line in Figure 5:

$$C = 12.3\ TI - 1.65 \quad \text{for } TI \geq 0.15 \tag{18}$$

In these equations V_b and TI are defined at 10% of the water depth above the bed.

7.3 Loose solid concrete blocks

1. The results of the present tests confirmed the findings of a previous research study carried out with loose solid concrete blocks (see Escarameia and May, 1992). The recommendation given then is therefore reiterated here in the form of the following safe-design equation which is a combination of Equations (14) and (15):

$$D_n = (9.22\ TI - 0.15)\ \frac{1}{s-1}\ \frac{V_b^2}{2g} \tag{19}$$

for TI ≥ 0.05 (5%)

In this equation V_b and TI are defined at 10% of the water depth above the bed.

7.4 Cabled blocks

1. Tests were carried out with scale models of cabled concrete blocks of the proprietary Armorflex type (see Figure 3). Three different levels of tension were applied to the cables from high tension to a situation where the blocks were tied together but not tensioned.

2. The amount of tension applied to the block mat does not appear to have a strong effect on the stability of a revetment such as Armorflex; this is likely to be partly due to the stretcher bond interlocking system present in this type of revetment.

3. It was found that a slightly higher stability is achieved when the cable direction is transverse to the main flow direction rather than when it is parallel to the flow.

4. As for the Reno mattresses tested, collapse was more easily achieved under normal turbulence conditions than under highly turbulent flows. In most cases the collapse involved failure of the leading edge of the block mattress by rotation or up-lifting; in the other cases lifting movements were observed in the centre of the mattress.

5. With no tension in the cables the Armorflex type revetment was found to be stable for mean flow velocities of at least 7m/s if the turbulance levels are low (typically less than 12%); in highly turbulent flows collapse was reached at a mean flow velocity of 2.8m/s.

6. The following safe-design equation is recommended for cabled concrete blocks with similar geometric characteristics to those of the blocks tested:

$$D_n = C\ \frac{1}{s-1}\ \frac{V_b^2}{2g} \tag{20}$$

where

C = 0.05 for TI ≤ 0.43 (43%)
and
C = 1.79 TI-0.72 for 0.43 < T1 ≤ 0.90

7.5 Interlocking blocks

1. The additional tests carried out with interlocking blocks (of the proprietary Armorflex type - see Figure 3) showed, as expected, greater stability than that of loose blocks under similar flow conditions. This is apparent in Figure 6 which also shows that the interlocking blocks were less stable than the cabled blocks tested. Due to the small number of data it was not possible, however, to establish a design equation.

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Tables

Table 1 Characteristics of the Reno mattresses tested

	Model 1:5 scale	Prototype values	Prototype Reno mattress
Mesh size (mm) *			
a	19	95	80
b	20	100	100
Cell dimensions (m)*			
l_1	0.50	2.5	2.0-3.0
l_2	0.20	1.0	1.0
l_3	0.06	0.3	0.3
Stone size (mm) d_{50}	23	115	125
Specific weight of stone (kg/m^{3})	2680	-	-
Voids ratio (e)	0.65	-	-

* See Figure 1

Table 2 Reno mattresses - High turbulence tests

Test	Mean flow velocity at 10% depth (m/s)		TI_u(10%) (%)	TI_w(10%) (%)	Flow depth y_0(m)	Mean flow velocity U(m/s)	Observations
	Streamwise, V_b	Vertical					
RH1	0.140	0.0098	39.6	11.5	0.130	0.190	No movement
RH2	0.095	0.0071	65.6	19.7	0.305	0.220	"
RH3	0.157	0.0066	52.2	15.7	0.310	0.350	"
RH4	0.245	0.0044	31.7	11.1	0.310	0.422	"
RH5	0.332	0.042	25.7	8.6	0.310	0.460	"
RH6	0.429	0.061	26.3	8.5	0.310	0.535	"
RH7	0.450	0.059	21.7	7.6	0.310	0.594	"
RH8	0.442	0.061	26.2	10.6	0.330	0.610	"
RH9	0.494	0.072	24.7	10.9	0.385	0.550	"
RH10	0.531	0.069	24.8	10.5	0.385	0.580	"
RH11	0.540	0.023	23.6	10.6	0.380	0.618	"
RH12	0.558	0.035	31.2	14.7	0.370	0.656	Small movement of rock within mattress $F_r = 0.344$
RH13	0.689	0.039	28.1	12.2	0.420	0.681	Small movement of rock within mattress $F_r = 0.335$
RH14	0.759	0.047	31.5	14.7	0.410	0.720	Small movement of rock within mattress $F_r = 0.359$
RH15	0.567	0.090	33.7	49.3	0.470	0.715	Movement of rock within mattress $F_r = 0.333$

Table 3 Reno mattresses - Rapid flow tests

Test	Mean flow velocity at 10% depth (m/s)		$TI_u(10\%)$ (%)	$TI_v(10\%)$ (%)	Flow depth y_o(m)	Mean flow velocity U(m/s)	Observations
	Streamwise V_b	Transverse					
RR1	1.59	0.130	19.5	9.0	0.145	2.00	No movement
RR2	1.66	0.133	18.6	9.0	0.150	2.02	"
RR3	1.79	-0.040	19.2	8.0	0.150	2.17	Movement of rock within mattress $F_r = 1.79$
RR4	2.00	0.064	15.4	7.2	0.130	2.51	Small movement of rock within mattress $F_r = 2.22$
RR5	2.33	0.240	16.3	11.3	0.140	2.46	Movement of rock within mattress $F_r = 2.01$

Table 4 Loose concrete blocks - High turbulence tests

Test	Mean flow velocity at 10% depth (m/s)		TI_u(10%) (%)	TI_w(10%) (%)	Flow depth y_o(m)	Mean flow velocity U(m/s)	Observations
	Streamwise, V_b	Vertical					
CL1	0.029	0.012	121.7	22.9	0.310	0.085	No movement
CL2	0.060	0.004	57.3	15.5	0.260	0.103	"
CL3	0.151	~0	32.5	8.8	0.255	0.259	"
CL4	0.272	0.012	24.3	4.6	0.240	0.381	"
CL5	0.278	0.011	22.5	1.8	0.255	0.378	"
CL6	0.353-0.430	0.020	23.3	3.0	0.260	0.498	"
CL7	0.482	0.015	19.4	4.6	0.255	0.508	"
CL8	0.456	0.016	23.5	5.3	0.255	0.533	Collapse $F_r = 0.337$

Table 5 Cabled blocks - Level of tension : A - High turbulence

Test	Mean flow velocity at 10% depth (m/s)			TI_u(10%) (%)	TI_v(10%) (%)	TI_w(10 %) (%)	Flow depth y_o(m)	Mean flow velocity U(m/s)	Observations
	Streamwise, V_b	Transverse	Vertical						
CHA1	0.915	-	0.047	26.8	-	7.3	0.220	0.546	No movement
CHA2	0.983	-	0.042	29.2	-	10.1	0.225	0.711	"
CHA3	0.966	-	0.073	51.2	-	12.6	0.355	0.819	"
CHA4	0.478	0.114	-	86.0	63.4	-	0.450	0.778	"
CHA5⊕	0.814	0.105	-	34.8	28.4	-	0.490	0.697	"

⊕ Cables in direction of flow

Table 6 Cabled blocks - Level of tension: A - Rapid flow

Test	Mean flow velocity at 10% depth (m/s)			TI_u(10%) (%)	TI_v(10%) (%)	TI_w(10%) (%)	Flow depth y_o(m)	Mean flow velocity U(m/s)	Observations
	Streamwise, V_b	Transverse	Vertical						
CRA1	2.10	-	0.0080	8.9	-	2.0	0.090	2.19	No movement
CRA2	2.38	-	0.0022	10.7	-	2.3	0.105	2.68	"
CRA3	1.89	0.181	-	11.4	6.4	-	0.120	2.74	Rotation of upstream row of blocks F_r = 2.52
CRA4	1.90	0.208	-	12.0	6.7	-	0.120	2.83	Rotation of upstream row of blocks F_r = 2.61
CRA5⊕	2.47	0.105	-	10.6	4.7	-	0.130	2.56	Some movement of upstream row of blocks F_r = 2.27

⊕ Cables in direction of flow

Table 7 Cabled blocks - Level of tension : B - High turbulence

Test	Mean flow velocity at 10% depth (m/s)		$TI_u(10\%)$ (%)	$TI_w(10\%)$ (%)	Flow depth y_o(m)	Mean flow velocity U(m/s)	Observations
	Streamwise, V_b	Vertical					
CHB1	0.194	0.117	69.1	39.2	0.195	0.726	Sand between blocks moved
CHB2	0.113	0.145	503	196	0.210	0.832	Sand between blocks was totally eroded

Table 8 Cabled blocks - Level of tension : B - Rapid flow

Test	Mean flow velocity at 10% depth (m/s)		TI_u(10%) (%)	TI_v(10%) (%)	Flow depth y_o(m)	Mean flow velocity U(m/s)	Observations
	Streamwise, V_b	Transverse					
CRB1	1.97	0.079	11.5	5.5	0.100	2.36	Upstream row of blocks lifted $F_r = 2.38$
CRB2	2.15	0.094	11.4	5.7	0.110	2.79	Small lifting of blocks at mid sections $F_r = 2.68$
CRB3	2.18	0.077	12.8	5.3	0.120	2.82	Small lifting of blocks at mid sections $F_r = 2.60$

Table 9 Cabled blocks - Not tensioned

Test	Mean flow velocity at 10% depth (m/s)		TI_u(10%) (%)	TI_w(10%) (%)	Flow depth y_o(m)	Mean flow velocity U(m/s)	Observations
	Streamwise, V_b	Vertical					
CH1	0.525	0.029	50.9	18.3	0.470	0.699	High turbulence test No movement
CH2	0.110	0.039	-	-	0.340	0.988	High turbulence test Collapse $F_r = 0.541$
CR1	-	0.037	-	-	0.080	2.49	Rapid flow test No movement

Table 10 Interlocking blocks (ARMORLOC) - High turbulence tests

Test	Mean flow velocity at 10% depth (m/s)		TI_u(10%) (%)	TI_w(10%) (%)	Flow depth y_o(m)	Mean flow velocity U(m/s)	Observations
	Streamwise, V_b	Vertical					
IB1	0.285	0.027	47.0	9.1	0.320	0.522	Total erosion of sand
IB2	0.451	0.046	74.5	24.9	0.370	0.627	Collapse $F_r = 0.329$

Table 11 Reno mattresses - Model and prototype values for critical movement condition

Test	F_r	U model (m/s)	U prot (m/s)	V_b model (m/s)	V_b prot (m/s)
RH12	0.344	0.656	1.47	0.558	1.25
RH13	0.335	0.681	1.52	0.689	1.54
RH14	0.359	0.720	1.61	0.759	1.70
RH15	0.333	0.715	1.60	0.567	1.27
RR3	1.79	2.17	4.85	1.79	4.00
RR4	2.22	2.51	5.61	2.00	4.47
RR5	2.01	2.46	5.50	2.33	5.21

Table 12 Cabled and interlocking blocks - Model and prototype values for failure conditions

Test	F_r	U model (m/s)	U prot (m/s)	V_b model (m/s)	V_b prot (m/s)
CRA3	2.52	2.74	7.75	1.89	5.34
CRA4	2.61	2.83	8.00	1.90	5.37
CRA5	2.27	2.56	7.24	2.47	6.99
CRB1	2.38	2.36	6.68	1.97	5.57
CRB2	2.68	2.79	7.89	2.15	6.08
CRB3	2.60	2.82	7.98	2.18	6.16
CH2	0.541	0.988	2.79	0.110	0.311
IB2	0.329	0.627	1.77	0.451	1.28

Figures

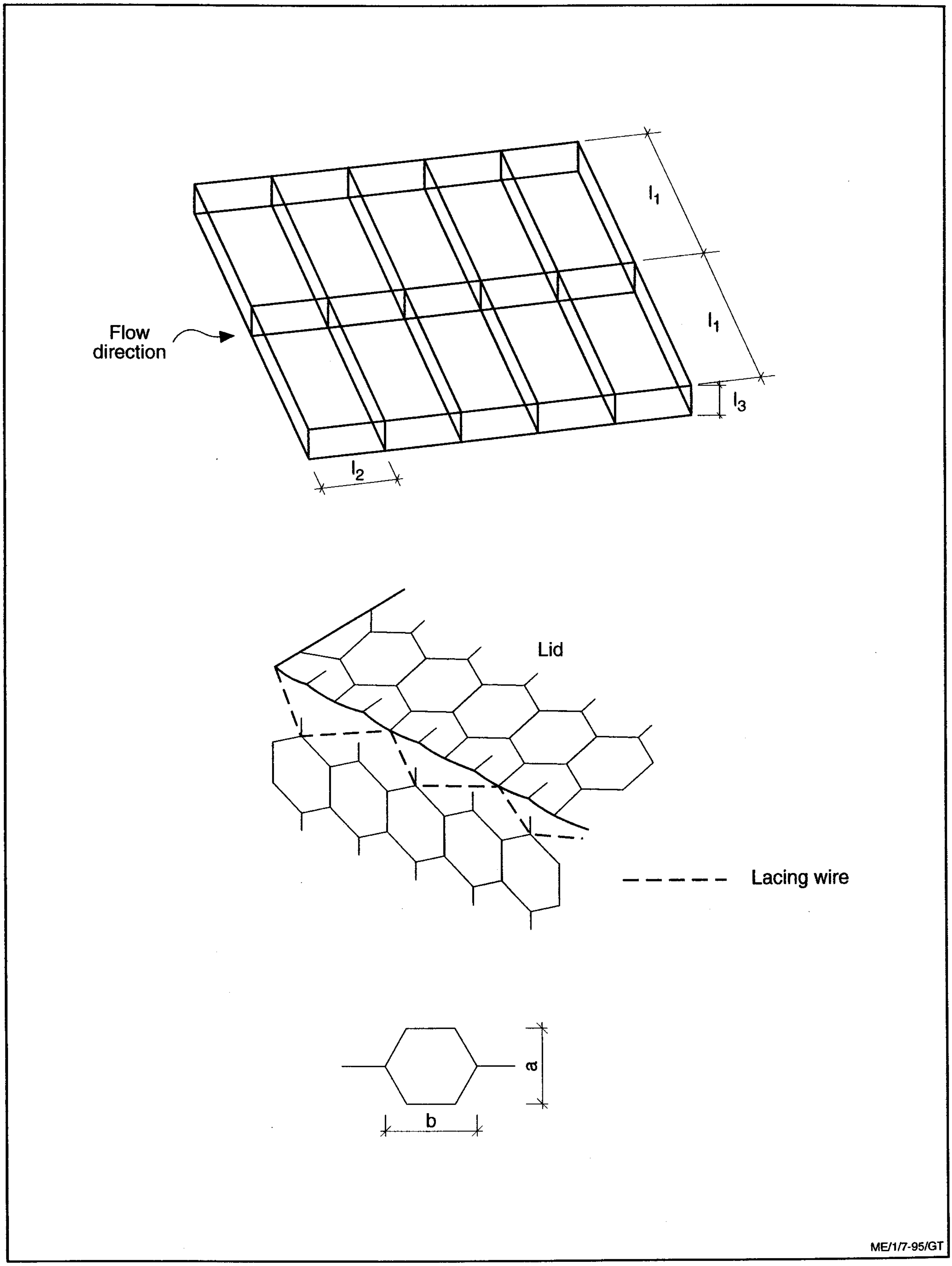

Figure 1 Geometric characteristics of Reno mattresses

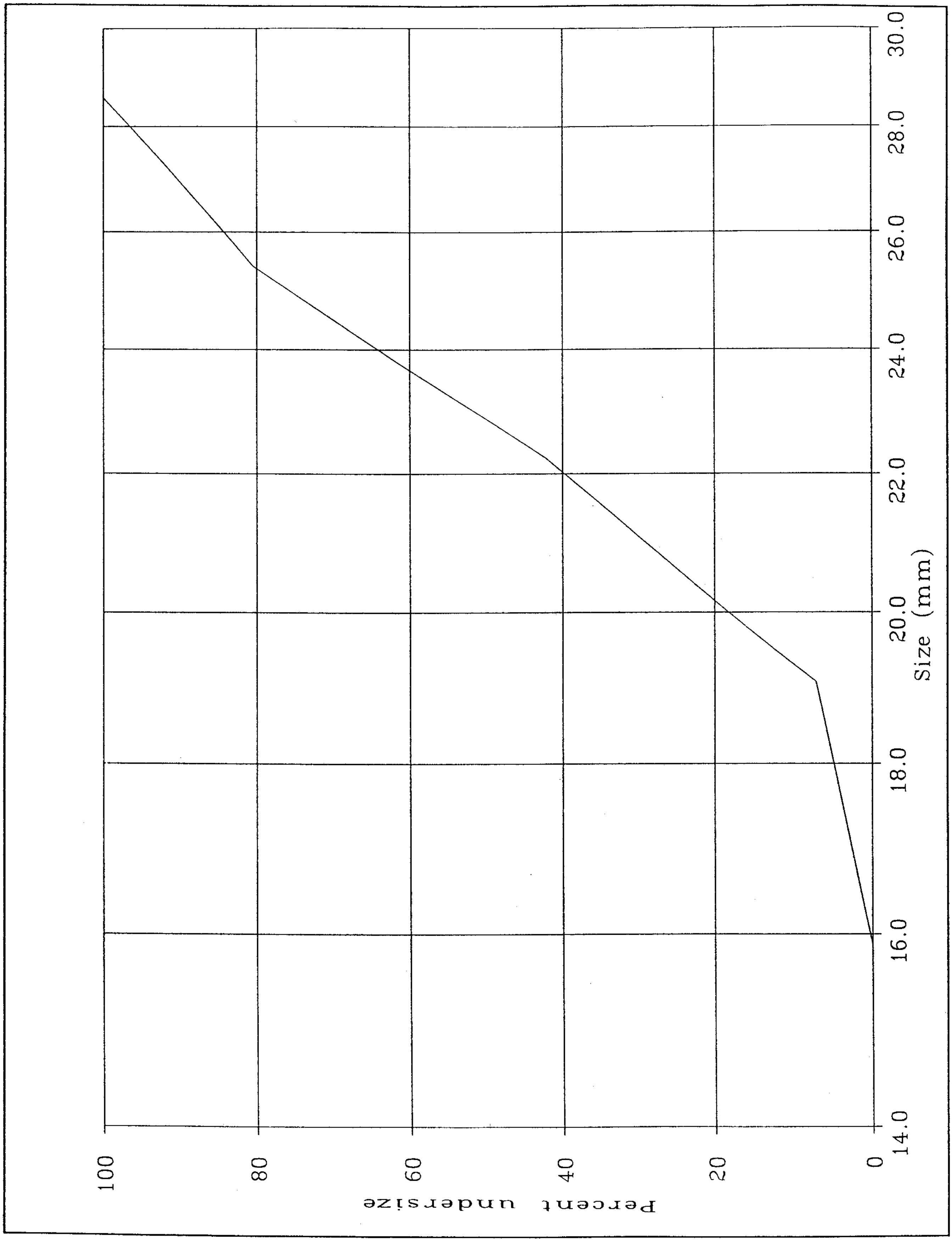

Figure 2 Grading curve of filling stone in the Reno mattresses

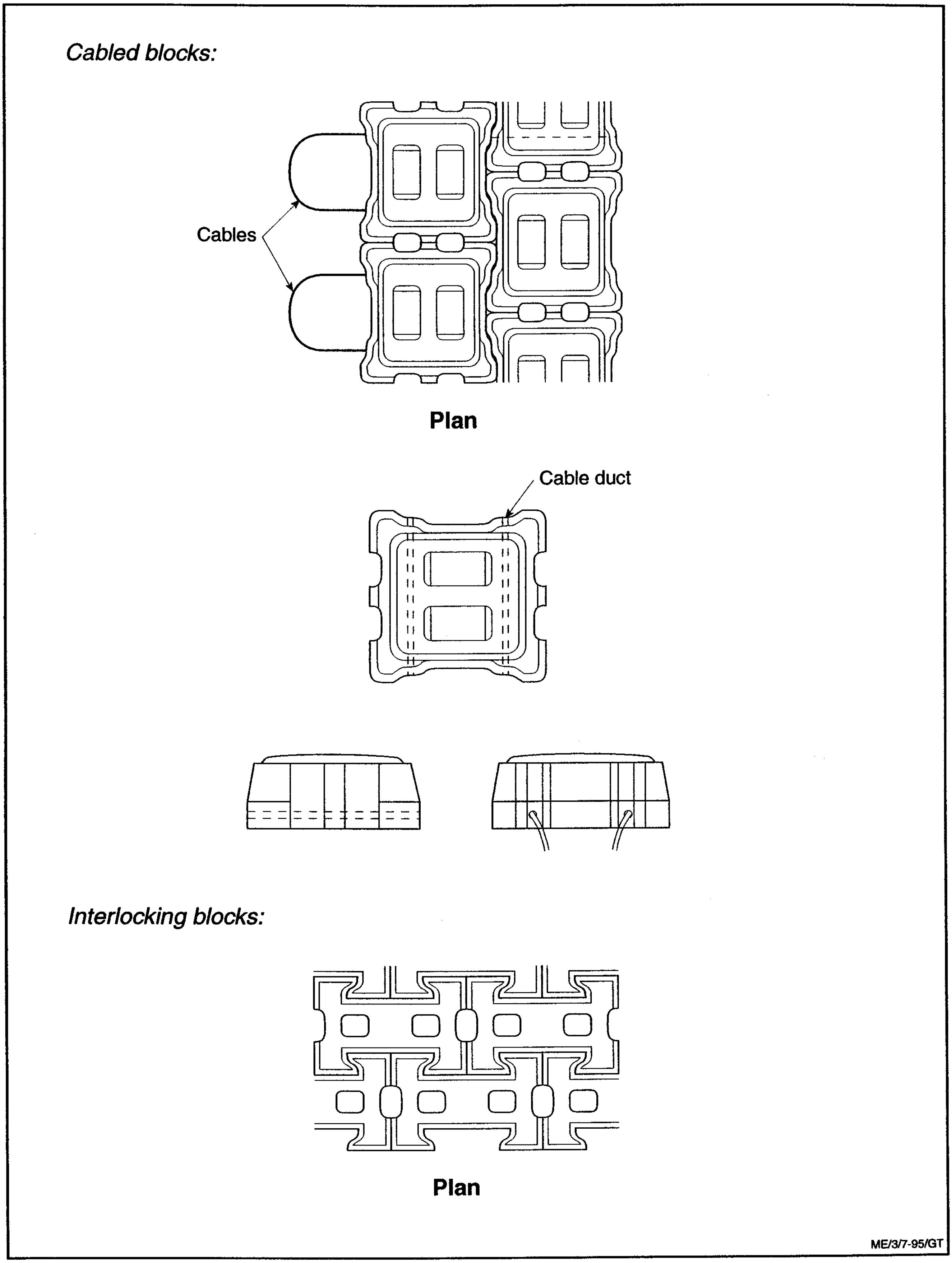

Figure 3 Geometric characteristics of cabled and interlocking blocks tested

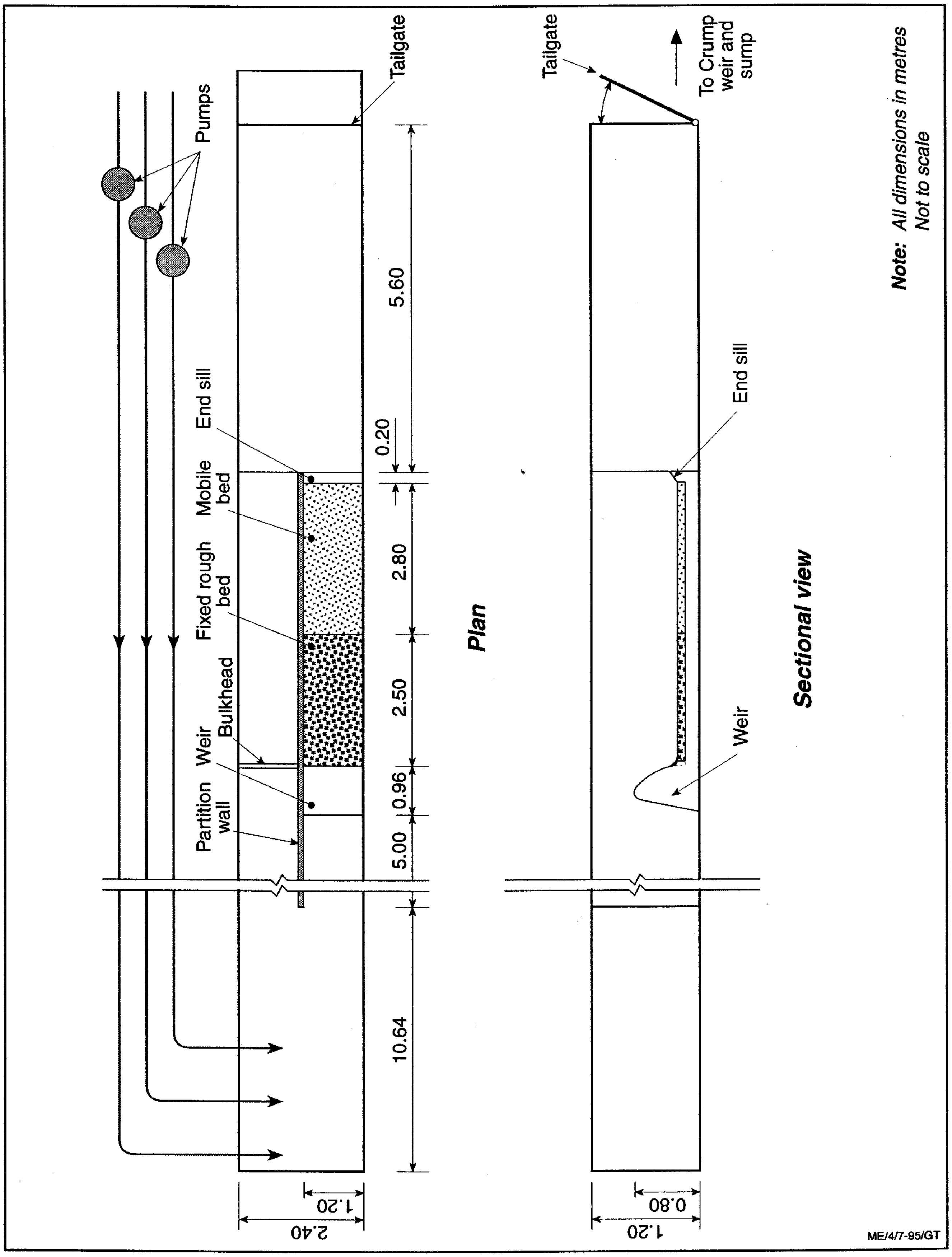

Figure 4 General layout of test rig

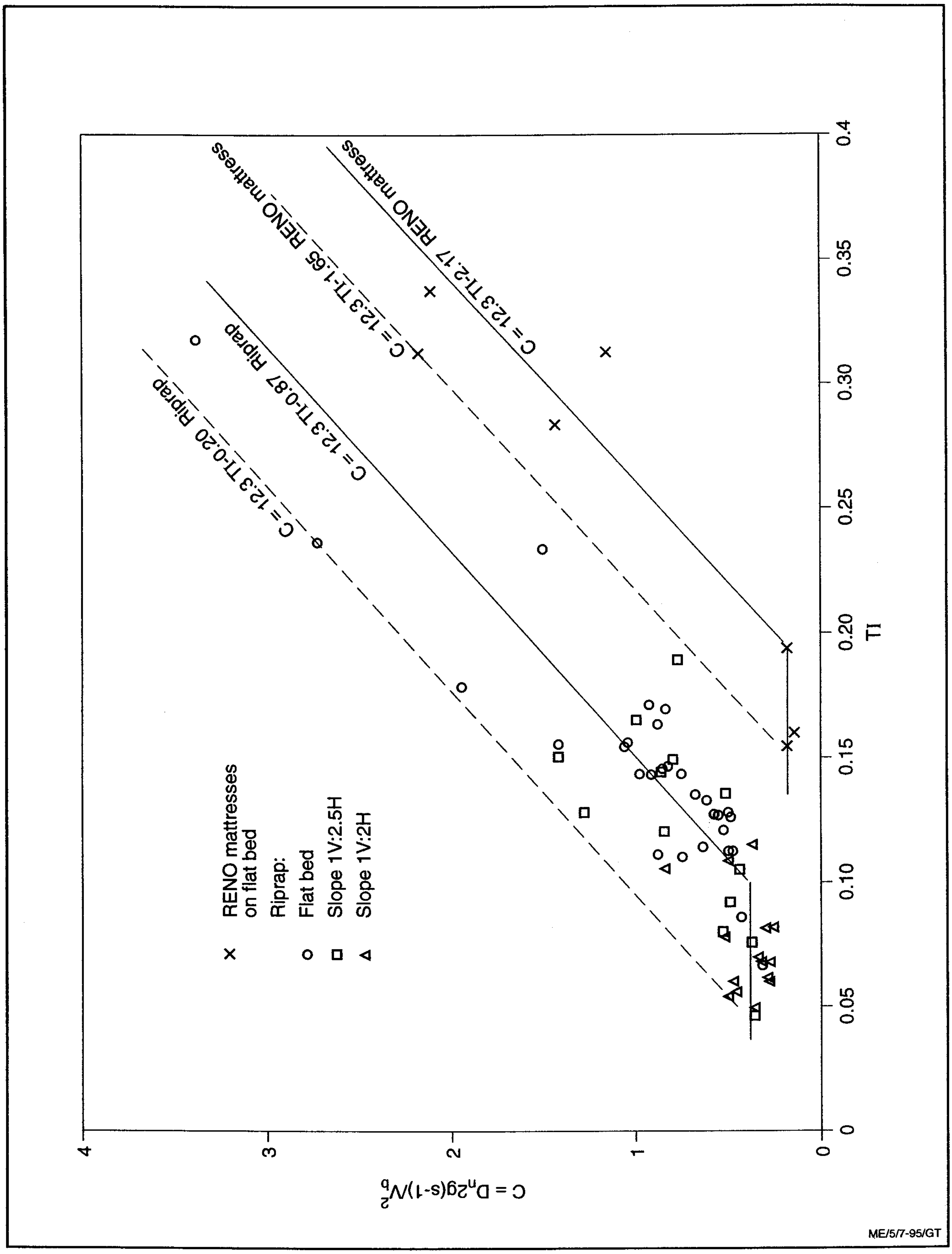

Figure 5 Relationship between C and the turbulence intensity for RENO mattresses compared with riprap

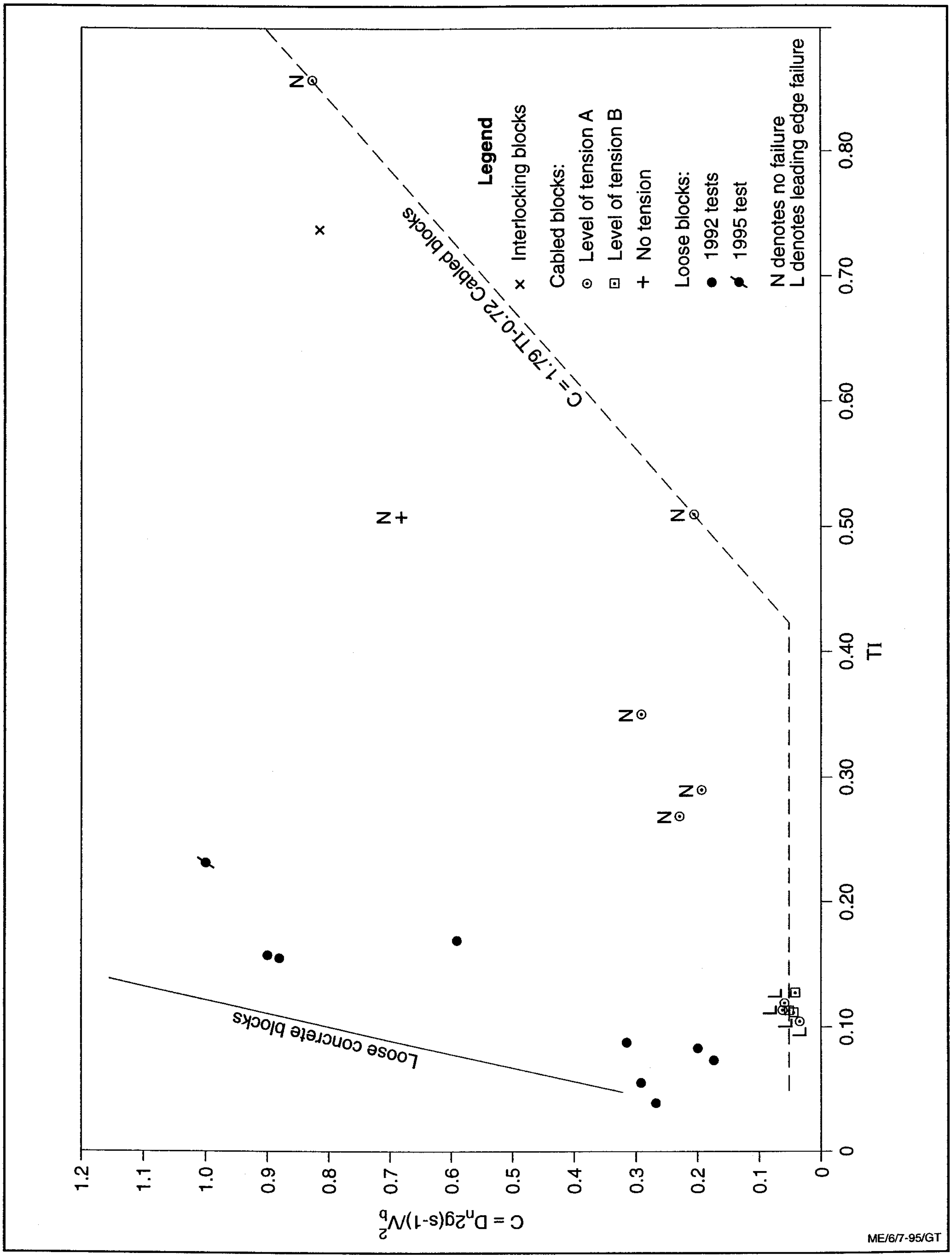

Figure 6 Relationship between C and TI for concrete blocks

Plates

Plate 1 Assembling of Reno mattresses

Plate 2 Reno mattresses placed in the flume

Plate 3 Reno mattresses in flume showing painted bands

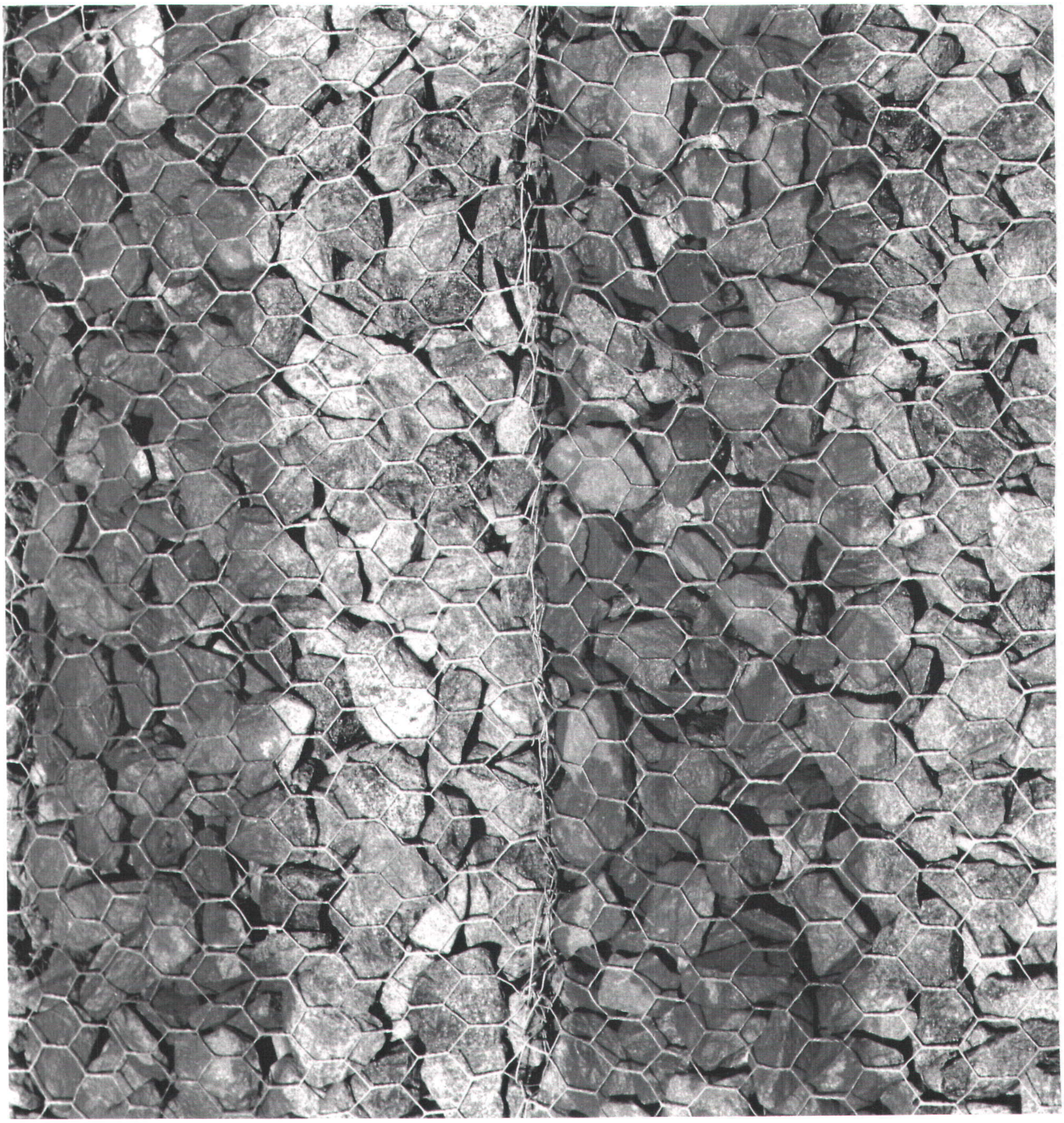

Plate 4   Reno mattress after a test showing movement of stone

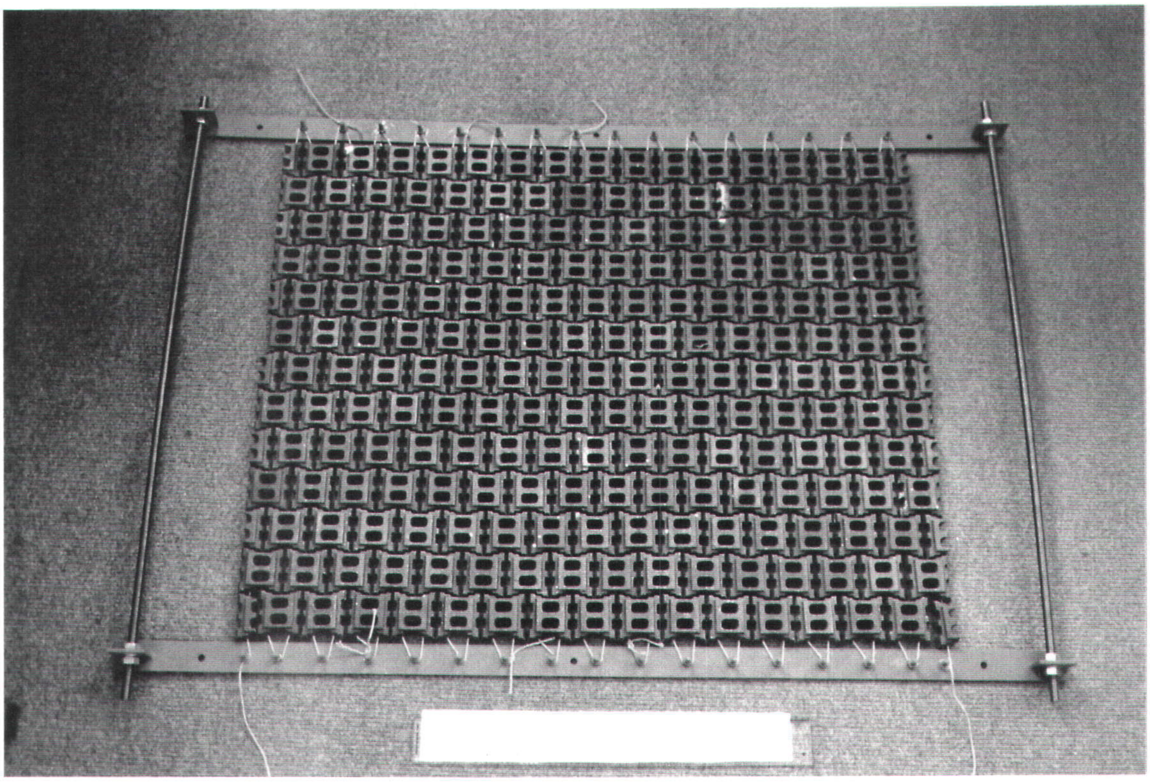

Plate 5 Cabled blocks with frame