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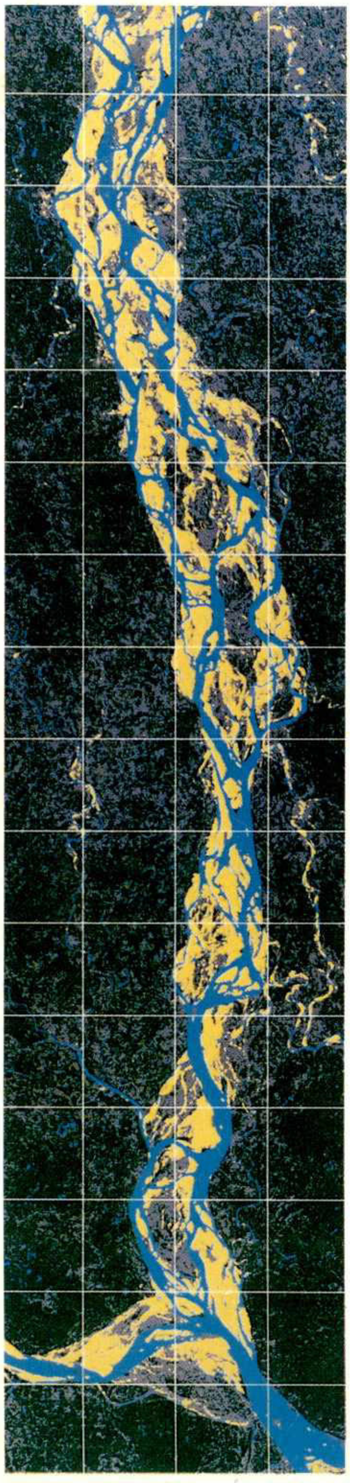

BANK PROTECTION AND RIVER TRAINING (AFPM) PILOT PROJECT FAP 21/22

TEST AND IMPLEMENTATION PHASE FAP 21

TECHNICAL REPORT NO. 4

FALLING APRON INVESTIGATION

MAIN REPORT

MARCH 1995

CONSULTING CONSORTIUM FAP 21/22

RHEIN-RUHR ING.-GES.MBH, DORTMUND/GERMANY

COMPAGNIE NATIONALE DU RHONE, LYON/FRANCE
PROF.DR. LACKNER&PARTNERS, BREMEN/GERMANY
DELFT HYDRAULICS, DELFT/NETHERLANDS

In association with:

BANGLADESH ENGINEERING & TECHNOLOGICAL SERVICES LTD.(BETS)
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FALLING APRON INVESTIGATION

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LIST OF SYMBOLS

A	=	Area of the block perpendicular to the approach flow direction	m^2
B	=	Size of the block	m
C_D	=	Coefficient of the draf force	-
c_1	=	Coefficient falling apron	-
F_D	=	Drag force on a block	N
F_g	=	Gravity force on the block	N
g	=	Acceleration by gravity	m/s^2
h	=	Water depth	m
q	=	Specific discharge	m^3/s
u	=	Approach flow velocity	m/s
T	=	Thickness of the falling apron	m
V	=	Volume of the falling apron	m^3
W	=	Width of falling apron	m
y_s	=	Maximum scour depth	m
ρ	=	Density of water	kg/m^3
ρ_s	=	Density of the blocks	kg/m^3

1 INTRODUCTION

One of the objectives of FAP 21 is to find improved solutions for river bank protection works against erosion by designing, specifying and constructing different types of groynes and revetments the behaviour of which will be monitored for a period of several years.

In the Planning Study Phase of the project physical model tests were performed to define the optimum alignment and layout of these test structures with respect to the maximum flow velocities and the scour holes in their vicinity. A field of 3 groynes was tested in a physical model at the River Research Institute (RRI), Faridpur, in 1992 and 1993, with variations of the type of groynes, their length, spacing and orientation to the flow. One of the most important results of these investigations was to realize that the scour depth at the head of permeable groynes is only 6 m compared with 20 to 30 m at the head of impermeable groynes with side slopes 1:3 and under average flood conditions. This phenomenon could be influenced by gradually increasing the spacing of piles of the permeable groynes between the bank and the head of the groyne.

Based on the results of these physical model tests it was decided to design a test structure of a series of 5 groynes at the right bank of the Jamuna river near Kamarjani. In this series of groynes one or two groynes have a falling apron to investigate the stability of the groynes by preventing the development of deep local scour holes.

A pilot project of a revetment was also tested in a physical model at the RRI. The side slope and several alignments of the upstream termination were tested for different approach channels. A preliminary design of a revetment was made to protect about 800 m of the bank with different types of protecting top layers, filters and falling aprons.

The type of falling apron studied in this investigation, is a heap of armour materials such as concrete blocks placed as an apron at the toe of a hydraulic structure. The function of these armour materials is to provide a protection of the lower part of the slope of a river bank while they creep, settle downwards along the slope of a developing scour hole. The scour can be in many places several meters below the original bed level.

In the physical model tests executed at the RRI a pre-shaped falling apron with a cemented surface was applied because the scale of the model did not allow a fair simulation of the creeping, settling armour materials. Therefore an additional investigation was proposed on the behaviour of falling aprons during a local scour process with emphasis on the scale effects and practical design rules for falling aprons as part of the test structures, because such sound and practical design rules do not exist in the literature at this moment, see Section 7.4.6 of the main report of the Planning Study Phase of the project.

This falling apron investigation was executed in a test facility of Compagnie Nationale du Rhône in France. This facility is located in a diversion channel of a dam in the Rhône river near Chanaz. The results of that investigation are presented in this report.

2 OBJECTIVES

An important objective of the falling apron investigation is to study the possible scale effects linked to the simulation of a falling apron in a physical model. Scale effects, which can lead to a deviation between the model and the prototype are mainly due to limitations to simulate the relevant hydraulic and morphological phenomena such as the hydraulic roughness, the size of the bed material and the sediment transport in the model according to the established laws of similitude.

Given the maximum available discharge in the diversion channel of about 8 m^3/s and the given width of that channel of about 20 m, the smallest scale factor for the geometry of the non-distorted model was determined at 15. The scale effects were then studied by changing the scale factor for the geometry from 15 to 25 and 50.

The main objective was to develop a design method for a falling apron made of cc-blocks as a toe protection of different types of groynes or revetments. The influence of different methods of placing the cc-blocks on the behaviour of a falling apron of different dimensions should be determined. This design method should be compared with existing methods.

An additional objective added during the execution of the tests was to increase the knowledge of the behaviour of cc-blocks dumped in flowing water. This can be important in case an emergency repair of a falling apron has to made during the monsoon flood.

3 MODEL FACILITY

3.1 Introduction

Details of the model facility which was used for this investigation of a falling apron around different river training structures are given in this chapter. The location and the plan of the model facility are described in Section 3.2. The scales selected in different tests were determined in view of the expected results of a test and are explained in Section 3.3. Some remarks on the particularities of the operation of the model are found in Section 3.4. In each test the same type of measurements and instruments were used according to a highly standardized measurement programme (see Section 3.5).

3.2 Description of the Model

A diversion channel of the Lavours dam in the Rhône river at Chanaz, about 120 km east of Lyon, France was very suitable for this physical model investigation, see map of the area in Figure 3.1. The total length of this straight channel is 130 m and its maximum width at the water level is 21 m. The steep banks of this channel have a slope of about 1:1 to 1:2 and the maximum water depth is about 1.5 m.

The flow entered the model through a pipe that connected the dam reservoir with the diversion channel. The available head difference between the reservoir and the model was sufficient to supply the required discharge by gravity. The pipe discharge was controlled by an intake gate. This diversion channel discharged in a pond which is linked to the Bourget lake and also to the Rhône river downstream of the dam.

This diversion channel which was used for the model, was divided in 3 sections, see Figure 3.2:
(a) an inflow section;
(b) a test section with a movable bed of a layer of fine sand. The movable bed section covered an area of about 675 m^2 and was filled with about 1500 m^3 of sand, and
(c) an outflow section between the tail gates and the movable bed.

Three sills were constructed in this diversion channel to raise the bed level in the test section. The elevation of the two most upstream sills is the same and they form the upstream and downstream boundary of the test section. On the third sill, which is the most downstream one, the tail gates were installed to control the water depth in the model. In the test section several types of river training structures were built on scale, such as groynes and revetments.

(i) Permeable and Impermeable Groynes
Two groynes were constructed by two parallel rows of PVC pipes with different diameters according to the scale factor for the geometry. The submerged part of the groynes was built according to the preliminary design of the groynes in the Final Planning Study Report, see Figure 3.3, which is a copy of Figure A.21-7 of Annexure 21 of that report. The pipes were placed to simulate the varying permeability from 70 % near the groyne head to 50 % near the bankline. The impermeable groynes were made by a vertical slab placed in front of the upstream row of the piles. Floating debris was modelled by some small branches and in another test schematized to a floating island of wood.

(ii) Cross-bar and Revetment
The cross-bar and the revetment were constructed in concrete and both had a side slope 1:3. The bank line upstream of the revetment was eroded over about 100 m. This resulted in an increased flow attack on the upstream termination of the revetment. The alignment of the revetment was straight and parallel to the main flow direction. The downstream termination of the revetment was close to the outflow section of the model and therefore it could not be tested.

Around these hydraulic structures falling aprons were placed made from cc-blocks ranging from 0.02 m to 0.08 m in model measures.

The model is an outdoor model which is subjected to changing climatic conditions, especially in the cold and rainy winter season. Because of the prevailing climate it was not possible to carry out tests from mid December to March. The study was performed from June to November 1993 and from April to July 1994. The model is located on the bank of the Rhône river and is affected by the floods in that river. Unfortunately, two important floods occurred in 1993 during the study period. Although the model site was not damaged by the floods, the water was dirty and the tests were temporarily stopped during these events.

3.3 Model Scale

For the study of a possible scale effect, it is preferred to vary the geometric length scale factor over a wide range and to keep this factor as small as possible. But a small length scale factor conflicts often with constraining design parameters for the facility. In the CNR facility, the maximum available discharge was around 8 m^3/s, which is an unusual high discharge for a physical model. In this facility the minimum value of the length scale factor was determined at 15, which is sufficient to permit precise measurements. Depending of the type of structure to be tested, the scale of the model was varied from 1 in 15 to 1 in 25. In one test a length scale of 1 : 50 was selected just to check the presence of a possible scale effect.

The main scale factors were deducted from the Froude law, which means that the value of Froude number in the model was equal to the value of the Froude number in prototype.

In an undistorted model in which sand is the bed material, the sediment transport can be reproduced at the right scale if the D_{50} is reproduced at the length scale of the model. However, the sand of the Jamuna river is so fine, see the sieve curve in Figure 3.4, that the diameter of the material to be used in the model should become equal to the diameter of silt or clay particles. But the behaviour of these materials is very different from the behaviour of sand and they cannot be used to simulate the sand transport in the model.

Moreover, the dimensions of the model and the use of natural river water, did not permit to use a material with a lower density than the density of sand. As a result, it was decided to use a sand having a grain size distribution similar to the grain size distribution of the Jamuna sand with a mean diameter as small as possible, see Figures 3.5 and 3.6. These two types of sand were used in different tests to evaluate a possible scale effect related to the sediment size. In test T1 the D_{50} of the sand was

1.4 mm and all other tests were done with the sand having a D_{50} of about 0.2 mm. The model sand was comparable with the Jamuna sand and also comparable with the sand used in the mentioned investigations in the River Research Institute.

The flow velocity in the Jamuna river is much higher than the critical flow velocity for the initiation of sediment motion, but that is no more the case in the physical model where the flow velocity is the prototype flow velocity divided by the velocity scale factor. The sand used in the model has a critical flow velocity for initiation of motion of around 0.2 m/s. The small length scale factor in the CNR facility resulted in a model flow velocity of around 0.5 m/s to 0.7 m/s when the Froude law was applied. These flow velocities were higher than about two times the critical velocity for initiation of sediment transport in the model. This ensured a fair simulation of the three-dimensional scour development around the considered river training structures. The main scale factors for the tests are summarized in Table 3.1.

Test	Parameters	Unit	Model	Prototype	Scale Factor
T1, T2, T3, T6, T7, T8, T9	length	m	37.5	563	15
	depth	m	0.67	10	15
	flow velocity	m/s	0.57	2.2	3.9
	discharge	m^3/s	7.5	6525	870
T4, T10	length	m	37.5	938	25
	depth	m	0.4	10	25
	flow velocity	m/s	0.54	2.7	5
	discharge	m^3/s	4.2	13125	3125
T5	length	m	37.5	1875	50
	depth	m	0.2	10	50
	flow velocity	m/s	0.48	3.4	7.1
	discharge	m^3/s	3	53250	17750
T11	length	m	37.5	938	25
	depth	m	0.4	10	25
	flow velocity	m/s	0.9	4.5	5
	discharge	m^3/s	7.2	22500	3125
T12, T13, T14, T15	length	m	37.5	938	25
	depth	m	0.6	15	25
	flow velocity	m/s	0.7	3.5	5
	discharge	m^3/s	5.8	18125	3125

Table 3.1: Hydraulic parameters in all the tests

3.4 Operation of the Model

The main parameters to be controlled in the model are the water level and the discharge. The discharge was estimated roughly by stream gauging in an undisturbed cross-section, because the intake gate was not calibrated. The water depth in the model was controlled by operating the tail gates at the downstream side of the model and the water level was measured by four point gauges in the model.

During a test some sand was eroded from the first 10 meters of the sand bed. Over an area of about 200 m^2, an additional layer of 0.20 m of sand was placed before each test. It was observed that during a test this area eroded gradually. It was checked that downstream of this 10 m, no general bed erosion occurred in most tests.

During a test the flow was almost steady, that means a fixed water level and discharge during the whole test. The model had been operated with a relatively high discharge to reproduce the local scour holes. The scour pattern around the test structures was reproduced in the sand bed of the model. In most cases, the equilibrium scour depth was obtained before the end of test run, this means that the scour depth did not increase after a certain time, usually after running the model 6 to 10 hours.

3.5 Measurements

Although it was tried to standardize the measurements in the tests it was often necessary to perform some special measurements in a particular test. The measurements which were made during a test are described in the following and summarized in Table 3.2.

- The water levels were measured by point gauges which were placed in the middle of the channel. The accuracy of the reading is estimated at about 2 mm.

- The flow velocities were measured in a standard cross-section and in the points of local grids around the tested river training structures. The flow velocity measurements were taken at 40% of the water depth measured from the bottom with small OTT-propeller flow meters, assuming that the depth averaged flow velocity occurs at that depth in a fully developed boundary layer of a uniform flow. The accuracy of the flow velocity measurement is estimated at 1 %.

- The flow lines around the tested hydraulic structures were determined by taking photographs with relatively long exposure times after spreading saw dust on the water surface and by keeping tracks of floating mobiles. These photographs were used for a qualitative analysis.

- The scour depths were also measured regularly by level instruments at standard cross-sections and at the points of the local grids around the river training structures as mentioned previously. The accuracy is estimated at about 0.01 m in vertical direction and 0.03 m in horizontal direction.

Parameter	Instrument
water level	point gauge
flow velocity	propeller meter
discharge	propeller meter and point gauge
flow lines	saw dust spreading
scour depths	level instrument
displacements of blocks	photographs, level instrument

Table 3.2: Different types of measurements

4 TEST PROGRAMME

The investigation focussed on studying the behaviour of a falling apron used as toe protection for different types of bank protection structures such as a permeable groyne, an impermeable groyne, a cross-bar and a revetment. In the test programme the size of the falling apron was varied in order to find design rules for falling apron around those bank protection structures. In total 15 tests were carried out, see for some characteristic parameters of these tests Table 4.1. It is mentioned that in tests T10 to T15 u/s and d/s can be replaced by right bank and left bank.

Test No.	Sand (D_{50}) (mm)	Structure		Scale of Model	Discharge of Model (m^3/s)	Falling apron used		Placing		Size of blocks used (cm, model)	
		u/s	d/s			u/s	d/s	u/s	d/s	u/s	d/s
T1	1.4	Per	Per	1 in 15	7.5	Yes	Yes	Uniformly	Uniformly	4x4x4	8x8x8
T2	0.2	Per	Per	1 in 15	7.5	No	No	-	-	-	-
T3	0.2	Per	Per	1 in 15	7.5	Yes	Yes	Uniformly	Uniformly	4x4x4	8x8x8
T4	0.2	Per	Per	1 in 25	4.2	Yes	Yes	Uniformly	Dumped	4x4x4	4x4x4
T5	0.2	Per	Per	1 in 50	3.0	Yes	Yes	Dumped	Dumped	4x4x4	2x2x2
T6	0.2	Per	Per	1 in 15	7.5	No	No	-	-	-	-
T7	0.2	Imp	Imp	1 in 15	7.5	Yes	No	Dumped	-	4x4x4	-
T8	0.2	Per	Per	1 in 15	7.5	No	No	-	-	-	-
T9	0.2	Imp	Imp	1 in 15	7.5	Yes	No	Dumped	-	4x4x4	-
T10	0.2	Per	Imp	1 in 25	4.2	No	Yes	-	Dumped	-	4x4x4
T11	0.2	Per	Imp	1 in 25	7.2	No	Yes	-	Dumped	-	4x4x4
T12	0.2	CB	Rev	1 in 25	5.8	No	No	-	-	-	-
T13	0.2	CB	Rev	1 in 25	5.8	Yes	Yes	Dumped	Dumped	2x2x2	1x1x1
T14	0.2	CB	Rev	1 in 25	5.8	Yes	Yes	Dumped	Dumped	2x2x2	2x2x2
T15	0.2	CB	Rev	1 in 25	5.8	Yes	Yes	Dumped	Dumped	2x2x2	2x2x2
Per = Permeable groyne; Imp = Impermeable groyne; CB = Cross-Bar; Rev = Revetment											

Table 4.1: Test programme

In the model only a limited area with a length of 500 to 1900 m and a width from 300 to 1200 m of the Jamuna river was modelled, because the scale factor for the geometry ranged from 15 to 50. As a consequence, no real bathymetry was moulded in the model, but a schematized straight channel with a flat, horizontal bed. The hydraulic design parameters as water levels and depth averaged flow velocities were reproduced at scale in the model. The hydraulic design parameters had been determined in the Final Planning Study Report, Main Report On Bank Protection, June 1993, in subsection 7.2, where for the series of groynes near Kamarjani and the revetment south of Bahadurabad the following hydraulic design parameters for an average return period of 2 years were mentioned:

- the average water depth is the water level minus the bed level:
  21.90 - 5.0 = 16.90 m around the groynes near Kamarjani,
  20.10 - 3.2 = 16.90 m along a revetment south of Bahadurabad,
- the depth averaged flow velocity varies between 2.0 and 2.5 m/s around the groynes in Kamarjani and 3.3 m/s along the revetment south of Bahadurabad.

In the model a water depth of 10 and 15 m was simulated and the cross-section averaged flow velocity varied between 2.0 and 4.5 m/s.

The fine sand of the Jamuna river can not be modelled at the length scale in the model. The difficulty to reproduce the bed material and the sediment transport can introduce a deviation between the model and the prototype what is called a scale effect. Some tests of the test programme were meant to determine the influence of possible scale effects. First, a series of two tests with a different grain size distribution were planned to estimate the influence of the bed material (T1 and T3). Moreover, the scale of the geometry was varied in several tests in order to make comparisons of the test results to detect a possible scale effect. These comparisons are the series T3/T4/T5 with T2/T10 and T9/T10 all with the same model sand.

In two tests, T2 and T12, no falling apron around the bank protection structures was placed to compare the results of these tests with the results of tests with a falling apron around permeable groynes, a cross-bar and a revetment.

To optimize the design of a falling apron around permeable groynes the layout of the protection, the number of blocks and their size were varied in the tests T3, T4, T5, T7 and T9. The effect of a reduced permeability by floating debris at the upstream side of a permeable groyne was studied in two tests, T6 and T8. It is mentioned that the flow velocity in T5 was greater than in the other tests because to simulate the development of local scour holes the model flow velocity had to be more than twice the critical velocity for initiation of sediment transport. This critical flow velocity was around 0,2 m/s in the model. The model flow velocity was chosen between 0,45 m/s and 0,50 m/s, this flow velocity was multiplied with the scale factor to obtain the resulting prototype velocity of 3,5 m/s.

The falling apron protecting an impermeable groyne in the shape of a vertical plate was studied in tests T7, T9, and T10. In general such a groyne generates a deep scour hole with steep side slopes.

The effect of an increased approach flow velocity upstream of a permeable groyne and an impermeable groyne was tested in T11. It is mentioned that the maximum velocity in the model was around 4.5 m/s and this is more than expected in prototype under design conditions. The results of this test were compared with the results of tests with a lower flow velocity.

A falling apron around the head of a cross-bar and along a revetment was investigated in tests T13 to T15 with a water depth of 15 m.

5 PRESENTATION OF THE RESULTS

A brief and systematic description of each test summarizes the objective, hydraulic parameters and the main results, see Appendix 1. The more complete results of the tests are presented in the referenced annexes, which form a separate volume of this report.

6 EVALUATION OF THE RESULTS

The results of the tests are presented per type of structure: permeable groyne, Section 6.2; impermeable groyne, Section 6.3; cross-bar, Section 6.4; and revetment in Section 6.5. Some special aspects of the results are possible scale effects, Section 6.1, the recommended design of a falling apron, Section 6.6 and the distribution of dumped concrete cubes on the bed, Section 6.7.

6.1 Scale Effects

6.1.1 Introduction

This Section deals with the differences between the physical model and the prototype as a result of a scale effect. In this physical model the main aspects of possible scale effects are related to the choice of the model sand and the scale of the geometry of the model. These aspects are described in Subsections 6.1.2 and 6.1.3 respectively. Finally the conclusions on these possible scale effects are summarized in Subsection 6.1.4.

6.1.2 Model Sand

Two tests (T1 and T3) were performed with two different grain size distributions of the model sand. In test T1 the mean diameter D_{50} of the sand was about 1.4 mm while it was 0.2 mm in T3. In Appendix 1 a detailed description of both tests is given.

In an undistorted model with a movable bed of sand, the sediment transport can be reproduced at scale in the model if the D_{50} is modelled at the length scale. However, the sand of the Jamuna river is so fine that the diameter of the material to be used in the model should become equal to the diameter of silt or clay. The properties of these materials are different from the properties of sand and therefore silt cannot be used to simulate the sediment transport in the model.

Therefore the selected movable bed material did not follow the laws of similitude. This can be accepted if the development of a local scour hole depends not strongly on the size of the bed material and the flow velocities in the model are sufficient high. In T1 and T3, the same permeable groynes were tested with the same falling aprons of uniformly placed cc-blocks. Some characteristic parameters of these tests are summarized in Table 6.1-1.

Parameters	Unit	T1	T3	Ratio T3/T1
D_{50} of model sand	mm	1.4	0.2	0.14
cross-section averaged flow velocity	m/s	2.2	2.0	0.91
max. flow velocity	m/s	2.4	1.9	0.79
max. scour depth u/s groyne	m	0.9	0.8	0.89
max. scour depth d/s groyne	m	0.6	0.9	1.50
height of ripples	m	0.05 to 0.06	0.04	0.67 to 0.8
length of ripples	m	0.8	0.2	0.25

Table 6.1-1: Comparison of tests T1 and T3

It is expected that possible scale effects will affect the flow pattern mostly, but also the scour pattern might be influenced by it. Therefore both aspects are described in the following.

(i) Flow Velocity and Flow Pattern
The flow velocities in test T3 were less than in T1 and the average flow velocity was reduced by about 10 % (see Table 6.1-1). The discharge was adjusted ensuring sufficient sediment transport in the model.

Nevertheless, qualitatively the flow distribution in the channel was similar in both tests. The qualitative observations of the flow pattern around the groyne shown with saw dust spreaded over the water surface did not show differences between the two tests. The flow was concentrated in the middle of the channel and the approach flow velocities upstream of the groyne were rather low. However, near the head of the groyne the reduction in the flow velocities was more than 10 %: the flow velocity in T3 was reduced with 20 % of the maximum flow velocity in T1, see Table 6.1. About half of this reduction might have been a scale effect.

(ii) Scour
After tests T1 and T3, the initial flat bed was transformed and covered with ripples. The change in sediment size resulted in a considerable reduction of the size of the ripples: 20 to 33 % in height and 75 % in length. This indicates a scale effect which influences the model roughness. Since the flow was guided largely by the banks of the straight channel this scale effect did not affect the model results too much.

The comparatively high maximum flow velocity near the head of the groyne caused a small increase of 10 % in the maximum scour depth around the upstream groyne. Although because of the presence of ripples the scour depth could not be measured accurately. The location of the maximum scour depth around the upstream groyne was the same in both tests (around 20 m d/s of the groyne, at 55 m from the bank). The results of both tests were also similar for the downstream groyne.

The behaviour of the falling apron was also the same in both tests. The falling aprons of uniformly placed blocks were stable and only very few blocks along the edge of the apron collapsed from the same location, see annex T1B and T3B.

(iii) Conclusion
The sediment size introduced a scale effect in the size of the ripples in the model bed. These ripples caused a scale effect in the hydraulic roughness of the model, what did not affect the overall flow pattern in a straight channel, but it probably did in the maximum flow velocity near the head of the groyne. The small scale effect in the maximum flow velocity might have induced a small scale effect in the maximum scour depth near the upstream groyne.

In general it is concluded that the overall flow pattern, scour development and the behaviour of the falling apron are only weakly dependent on the sediment size of the movable bed. Nevertheless, only more specific investigations should be able to quantify the scale effect of the model sand accurately.

6.1.3 Scale of the Model

(i) Introduction
In the CNR facility three different values of the scale factor for the geometry were tested, 15, 25 and 50, to identify possible scale effects due to the scale of the model. It is important to know whether a falling apron can be tested without serious scale effects at a scale 1 in 50 with rather small cc-blocks.

As mentioned previously in the tests T2 to T15 the same sand was used in the movable bed, therefore the comparisons of the results of these tests are not biassed by a possible scale effect by different types of model sand. The model sand is comparable with the Jamuna sand with D_{50} = about 0.18 mm.

Three different series of tests were executed to provide some guidelines concerning the influence of the scale of the model:
- 1st series: permeable groyne with falling apron, T3, T4, T5 (para ii);
- 2nd series: permeable groyne without falling apron, T2, T10 (para iii), and
- 3rd series: impermeable groyne with and without falling apron, T9, T10 (para iv).

(ii) First Series: Permeable Groyne with Falling Apron

In the three tests of this series the scale factor of the geometry varied from 15, 25 to 50 (T3, T4 and T5). In these tests two permeable groynes were tested with a falling apron around the toe of the piles. The block size of the falling apron and the method of placing these blocks were varied from test to test, see Table 6.1-2, and details of those tests are described in Appendix 1.

Parameters	T3	T4	T5
Model scale Velocity (m/s)	1/15 2.2	1/25 2.7	1/50 3.4
Structure Permeability (%) Falling apron	Perm. groyne 70,70,60,50 Yes	Perm. groyne 70,70,60,50 Yes	Perm. groyne 70,70,60,50 Yes
Block size (cm, model) u/s groyne d/s groyne	 4x4x4 8x8x8	 4x4x4 4x4x4	 4x4x4 2x2x2
Way of placing u/s groyne d/s groyne	 Uniformly Uniformly	 Uniformly Dumped	 Dumped Dumped

Table 6.1-2: Main parameters of tests T3, T4, T5

It is expected that possible scale effects influence both the flow pattern and the development of local scour holes. Therefore both aspects are described in the following.

- Flow Velocities and Flow Pattern

Some profiles of the depth averaged flow velocity around the upstream and the downstream groynes are compared in Figures 6.1-1 and 6.1-2 to analyze the flow distribution around the groynes. Some measurements are missing in T5 near the groyne, because the dimension of the propeller of the flow meter was too big. It might be that some flow velocities were influenced by the placement of the OTT propeller meter behind or in between piles of the groyne. Nevertheless, these flow velocity profiles measured in T3 to T5 show the same tendencies for the upstream groyne 1 with differences on average 0.2 m/s and maximum 0.4 m/s.

It is mentioned that the flow velocities in tests T3 and T4 were scaled according to the Froude condition. However, in test T5, the flow velocities were increased to 0.5 m/s in the model to create sufficient sediment transport and the Froude condition was not respected. The cross-section averaged flow velocity was constant in those tests (0.57, 0.54 and 0.48 m/s), but the water depth varied 0.67, 0.40 and 0.20 m respectively. These variations in the water depth affects the distribution of the hydraulic roughness and consequently the flow pattern.

Qualitatively the overall flow pattern was the same in those tests. The permeable groynes induced only a very slight deviation of the flow downstream of the groynes. The flow lines were following the left bank, passing through the permeable groynes. The flow velocity was reduced from the head of the groyne to the bank. The scale of the geometry in the range of 15 to 50 did affect the flow pattern slightly.

- Scour

In all three tests the scour was situated in the vicinity of the groyne and the maximum scour depth was observed about 20 m downstream of the head of the upstream groyne. Some scattering in the location of the maximum scour depth around the downstream groyne was found. However, the maximum scour depth was rather small in those tests, see Table 6.1-3. The randomly dumped cc-blocks in T5 have increased the hydraulic roughness of the falling apron compared with the uniformly placed cc-blocks in the other tests. The increased hydraulic roughness had limited the local scour depth to 0.03 m model value.

In the tests with a falling apron of uniformly placed blocks a smaller water depth and the same flow velocities resulted in 100 % deeper scour holes. This tendency can be explained by the vertical flow velocity profile which indicates higher shear stresses if the water depth is reduced and the depth averaged flow velocity is kept constant.

In fact, with the permeable groynes in this series of tests, the scour depth was small and comparable to the height of the bed ripples, which was the same in T3, T4 and T5. Taking into account the accuracy of the small scour holes it appears that the tendency in the local scour depth as a function of the scale of the model is not clear, but it seems that the scale factor for the geometry has a scale effect on the maximum scour depth.

Test	Scale factor	Water depth (model) (m)	Averaged flow velocity (m/s)	Placement of falling apron	max. scour depth (model) (m)	max. scour depth (proto) (m)
T3	15	0.67	0.57	uniform	0.05	0.8
T4	25	0.40	0.54	uniform	0.10	2.5
T5	50	0.20	0.48	dumped	0.03	1.4

Table 6.1-3: Maximum scour depths and some characteristic parameters in T3, T4 and T5

- Conclusion

The scale of the geometry in the range of 15 to 50 did affect the flow pattern slightly and it seems that the scale factor for the geometry has a scale effect on the maximum scour depth. The results of the tests show also the importance of scaling the hydraulic roughness according to the laws of similitude for this physical model investigation.

- Second Series: Permeable Groyne without Falling Apron

A permeable groyne without a falling apron was tested in T2 and T10 which were exactly the same tests, except the scale factor for the geometry was different: 15 in T2 and 25 in T10.

In both tests the overall flow pattern was similar and the velocity measurements did not show scale effects in the flow velocity distribution downstream of the groyne, but in T10 the approach flow velocity distribution in cross-section 1 was different in both tests. Probably, the inflow of the model was not perfect in that test and this disturbs the comparison of the results of both tests.

The scour was concentrated around the toe of the piles in both tests. The maximum scour depths are listed in Table 6.1-4. In T2, the scour developed along the whole length of the groyne, while in T10 the scour was increased in the middle of the groyne where the permeability was less and the approach flow velocity relatively high. Therefore it is not possible to conclude on the presence of a scale effect in these tests.

Test	Scale factor	Water depth (model) (m)	Averaged flow velocity (m/s)	Max. scour depth (model) (m)	Max. scour depth (proto) (m)
T2	15	0.67	2.2	0.11	1.7
T10	25	0.40	2.7	0.12	3.1

Table 6.1-4: Scour depths and some characteristic parameters in tests T2 and T10

(iv) Third Series: Impermeable Groyne with and without Falling Apron

In this series an impermeable groyne in the shape of a vertical plate was tested. This groyne was protected with a thin and small falling apron, composed of a single layer of cc-blocks of 4x4x4 cm, model value. The main parameters of the tests T9 and T10 are given in Table 6.1-5 and more details are presented in Appendix 1.

It is expected that possible scale effects will affect the scour pattern as well as the flow pattern. Therefore both aspects are discussed separately:

- Flow velocities and flow pattern

The comparison of flow velocity profiles in different sections in T9 and T10 show a reasonably good correlation, see Figures 6.1-3 and 6.1-4. Qualitatively the typical flow pattern around impermeable groynes is also comparable in both tests, see annex T9E showing the flow field around the impermeable groyne in T9 with the flow velocities measured.

However, the differences in the cross-section averaged flow velocity reflect the differences in cross-section 1 in both tests. The comparison of the flow pattern would have been more accurate if the flow velocity distribution in the inflow of the model was more precisely controlled.

- Scour

The maximum scour depths in both tests are almost the same in prototype values, see Table 6.1-5. And the differences in the location of the maximum scour depth relative to the head of the groyne are less than 5 m.

In the model, the scour hole was much deeper than the height of the ripples. In both tests the scour hole extended to the area upstream of the groyne, just around its head. The results of these tests show that the scale of the model does not affect the location and the maximum scour depth around an impermeable groyne shaped as a vertical plate.

Test	Scale factor	Water depth (model) (m)	Averaged flow velocity (m/s)	Max. scour depth (model) (m)	Max. scour depth (proto) (m)
T9	15	0.67	2.2	0.70	10.5
T10	25	0.40	2.7	0.40	10.1

Table 6.1-5: Scour depths and some characteristic parameters in tests T9 and T10

6.1.4 Conclusion

A deviation from the condition that the sediment size should be scaled on the length scale had introduced a scale effect in the size of the ripples in the model bed. These ripples caused a scale effect in the hydraulic roughness of the model, what did not affect the overall flow pattern in a straight channel, but it probably did in the maximum flow velocity near the head of the groyne. The small scale effect in the maximum flow velocity might have induced a small scale effect in the maximum scour depth near the upstream groyne.

The scale of the geometry in the range of 15 to 50 did affect the flow pattern around a permeable groyne with a falling apron slightly and it seems that the scale factor for the geometry has a scale effect on the maximum scour depth. In a movable bed model the development of ripples cannot be controlled. The distribution of the ripples over the bed determines the hydraulic roughness and its often not-uniform distribution over the channel bed. Changes in this hydraulic roughness will change the flow pattern if the boundary layer is fully developed and the flow is not largely guided by the banks. This model was rather short and the flow was guided to some extend by the banks, therefore the scale effect was rather small. This result shows also the importance of scaling the hydraulic roughness according to the laws of similitude for testing permeable groynes.

However, no scale effect could be determined in the flow pattern and the scour holes around an impermeable groyne made of a vertical plate. The flow pattern around this groyne was almost completely determined by the geometry of the groyne and not by the hydraulic roughness of the upstream channel bed.

The conclusion is that the deviation from the ideal sediment size and varying the length scale introduce small or moderate scale effects in a model with permeable groynes, but in a model with impermeable groynes these scale effects will be neglectable.

6.2 Permeable Groyne

6.2.1 Introduction

The purpose of the river training structure along the bank of the Jamuna river near Kamarjani is to stabilize the bank erosion by reducing the flow velocity near the bank. In the former physical model study in the River Research Institute permeable groynes were selected as bank protection because of their efficiency to limit the flow velocity along the bank and because of the smaller scour depths induced by it than by impermeable groynes.

This Section deals with the efficiency of a permeable groyne to reduce flow velocities and local scour depths (Subsection 6.2.2), the size and type of falling apron protecting a permeable groyne (Subsection 6.2.3) and the effect of floating debris on scour depths and flow velocities around a permeable groyne (Subsection 6.2.4).

6.2.2 Permeable Groyne Efficiency

In different tests permeable groynes were tested under moderate and extreme hydraulic conditions, while the water depth was kept constant at 10 m, which is a moderate water depth. These moderate conditions can be expected to occur during the monitoring period, while the extreme conditions are a check on the sensitivity of the model results for changing hydraulic conditions.

(i) Moderate flow attack

The aim of a test with a permeable groyne not protected by a falling apron (T2 and T10) was to compare the results of these tests with the results of other tests with falling aprons. The main difference between T2 and T10 is the different length scales 15 and 25. The effect of a permeable groyne on the flow pattern and the development of local scour near the groyne under moderate hydraulic conditions are discussed in the following.

- Flow velocities and flow pattern

Close to the bank, over a distance of about 6 to 9 m, the bed was flat in T2 without any ripples indicating that the flow velocities were reduced along the bank. No eddies developed in between the two groynes and the flow lines were more or less parallel to the bank in that area.

A maximum flow velocity of 2.0 m/s (T2) and 2.6 m/s (T10) was measured at the head of the upstream groyne 1. In between the two rows of piles, the flow was accelerated slightly up to around 2.2 m/s in T2 and decelerated to 2.1 to 2.3 m/s in T10.

Distance form the toe of the left bank	Depth averaged flow velocity in a cross section 15 to 22.5 m downstream of the groyne in T2 and T10	Depth averaged flow velocities in upstream cross-section 1
(m)	(prototype m/s)	(prototype m/s)
3.0	0.6	
7.5	1.2	
15.0	1.4	2.0
22.5	1.5 to 2.2	
30.0	1.6 to 2.5	
37.5	1.5 to 2.5	
45.0	1.6 to 2.7	2.1
52.5	2.0 to 2.8	

Table 6.2-1: Depth averaged flow velocities upstream and downstream of groyne 1 in T2 and T10

- Scour

The maximum scour depth of 1.7 m (T2) and 2.0 to 3.1 m (T10) developed along the toe of the piles of the upstream groyne 1. The scour around the downstream groyne 2 in T2 was small, because the approach flow of that groyne was reduced by the upstream groyne 1.

(ii) Extreme Flow Attack

The cross-section averaged flow velocity was increased from 2.5 m/s in T10 to 4.2 to 4.5 m/s in T11. The approach flow to the groyne was also increased resulting in a stronger flow attack on the groyne. It is mentioned that these two tests were performed at a geometric length scale 1 in 25, see the detailed description of these tests in Appendix 1.

- Flow velocity and flow pattern

The maximum flow velocity measured between the piles of the groyne increased from 2.3 m/s in T10 to 3.2 m/s in T11 and near the groyne head the maximum flow velocity increased from 2.8 m/s to 4.0 m/s. Nevertheless, the overall flow velocity distribution and the flow pattern around the groynes were equivalent in both tests.

- Scour

The maximum scour depth near the permeable groynes was almost equal in both tests T10 and T11 (3.1 m after T10 and 3.7 m after T11). That means that the scour around the permeable groyne was slightly depending on the flow velocity: a 20 % increase of the maximum scour depth because of a 20 to 25 % increase of the maximum flow velocity near the piles of the groynes.

The analysis of a large number of tests on local scour around bridge piers has resulted in a fair estimation of the maximum scour depth by a rule of thumb (see Breusers, Nicollet and Shen, 1977): for a cylindrical pile with a diameter D, the maximum scour depth varies between 2 D and 3 D, provided the approach flow velocity exceeds 1.5 to 2.5 times the critical flow velocity for the initiation of movement of the bed material. This rule indicates also that the scour depth does not increase with an increase of the approach flow velocity if a certain minimum flow velocity is surpassed.

The considered permeable groyne consisted of one or two rows of piles with a diameter of 1 m. If each pile was alone in the flow, the expected maximum scour depth should vary between 2 and 3 m. Therefore it is not surprising to find scour holes of 3 to 4 m if the effect of two rows of piles is taken into account. The maximum scour depth induced by a permeable groyne is much less than the maximum scour depth developed around an impermeable groyne. The maximum scour depths obtained in the model do not contradict the well established rule of thumb for the maximum scour around a single cylindrical pier.

6.2.3 Falling Apron Protecting a Permeable Groyne

Different types of falling aprons to protect a permeable groyne made of piles were simulated in tests T1 to T5 as indicated in Table 6.2-2. The falling apron was always stable during those tests and very few blocks fell down along the edge of the uniformly placed apron. The dumped blocks of the falling apron increased the roughness of the bed around the groyne, leading to sand deposition on the top layer of the falling apron. On top of the uniformly placed blocks also some deposition of sand was observed after completion of the test. This sand was transported from the bed upstream of the groynes.

Some artificial damage of a uniformly placed falling apron was tested in T3 by removing some blocks from it at three places. This artificial damage in the uniformly placed blocks did not increase the damage on the protecting apron.

These tests proved that the use of a falling apron of dumped blocks around the piles of a permeable groyne can be an effective protection against the development of scour holes under moderate hydraulic conditions (especially 10 m water depth).

Test No.	Type of groyne		Scale of model	Width apron (m)				Placing		Layer thickness		Size of blocks used (cm, model)	
	u/s groyne 1	d/s groyne 2		u/s groyne 1 u/s	d/s	d/s groyne 2 u/s	d/s	u/s gr.	d/s gr.	u/s gr.	d/s gr.	u/s gr.	d/s gr.
T1	Per	Per	1 in 15	10	15	10	15	Uniformly	Uniformly	2	2	4x4x4	8x8x8
T2	Per	Per	1 in 15	-	-	-	-	-	-	-	-	-	-
T3	Per	Per	1 in 15	10	15	10	15	Uniformly	Uniformly	2	2	4x4x4	8x8x8
T4	Per	Per	1 in 15	10	15	10	15	Uniformly	Dumped	2	2	4x4x4	4x4x4
T5	Per	Per	1 in 15	10	15	10	15	Dumped	Dumped	2	2	2x2x2	2x2x2

Table 6.2-2: Falling apron placed around the permeable groynes

6.2.4 Floating Debris

The efficiency of a permeable groyne depends on the permeability of the groyne which can create a smooth gradient in the flow velocities from the head of the groyne to the bank. But, if the permeability of the groyne diminishes than the scour could increase and the stability of the groyne can become endangered. In practice the up-piling of floating debris at the upstream side of the groyne can cause such a reduction of the permeability of the groyne. The possible effect of floating debris trapped in the piles was tested in T6 and T8.

A limited blockage over a length of 20 m and a depth of 2 m around the head of the groyne was modelled in T6, while in T8 an important amount of floating debris, especially tree trunks, was accumulated upstream of the groyne over its whole length and with a thickness of about 2 m.

The effects of floating debris on the flow pattern and on the local scour depths are estimated by comparing tests T2, with no floating debris with tests T6 and T8 in the following paragraphs. It is mentioned that a falling apron was not modelled in all these tests.

(i) Flow Velocities and Flow Pattern
It is expected that the diversion of the flow around the obstacle created by floating debris will accelerate the flow locally. However, the increase of the measured flow velocities was only noticeable along the sides of the obstacle in T6 and it was still very limited from 1.4 m/s in the approach flow to maximum 1.7 m/s under the obstacle. This can be explained by the continuity of the specific discharge along a flow line: $q = 1.5 * 10 = 1.7 * (10 - 2 + 0.8) = 15.0\ m^2/s$. The specific discharge is the undisturbed water depth - depth of the blockage + local scour depth multiplied by the depth averaged flow velocity. This shows that the local scour reduces the increase of the flow velocities under the obstacle. But if a falling apron or a bed protection is applied the local scour near the groyne is zero and the increase in the flow velocity will be more than in T6.

A blockage over the full length of the groyne as in T8 forces the surface flow not to pass through the groyne but to be diverted partly towards the head of the groyne as if the groyne was impermeable, and partly to dive under the debris, mainly tree trunks. This vertical flow pushed down some of the tree trunks and some of them reached the toe of the piles. This process continued as long as the new tree trunks arrived from upstream and gradually the thickness of the layer of trunks trapped upstream of the groyne increased. In the Jamuna river the banana tree trunks are mixed with water hyacinths and other plants preventing the banana trees to be pushed down.

The maximum flow velocity near the groyne increased 10 to 15 % from 2.1 to 2.4 m/s with the floating debris. When new trees were reaching the groyne, these percentages did not change significantly probably because of the increase in the local scour depth. The flow velocities near the bed had a tendency to increase with about 0.3 m/s as the blockage increased. This indicates that the discharge passing under the floating debris was reduced and more water diverted to the head of the groyne.

(ii) Scour
Comparing the maximum scour depths in T6, T8 and in T2, Table 6.2-3, it is concluded that the floating debris caused a small increase in the maximum scour depths observed near the base of the piles. The small increase in the flow velocities caused a small increase in scour depths of about 1 m under moderate hydraulic conditions.

In T8, the maximum scour depth of 2.7 m developed along the toe of the piles. But, some scouring also occurred downstream of the groyne head. The floating debris caused a partially blocked permeable groyne to function partly as a permeable and partly as an impermeable one.

Although in practice the percentage of blockage may be greater than in T6 and T8 and probably creating more severe effects on the scour depths and the flow velocities, it is expected that floating debris does not create a problem for the test structure under the moderate flow conditions (water depth is 10 m only).

Test	Blockage by debris	Maximum flow velocity near groyne	Maximum scour depth near groyne
-	(%)	(m/s)	(m)
T2	0	1.7 to 2.2	1.7
T6	10	2.2	2.5
T8	40	2.4	2.7

Table 6.2-3: Maximum flow velocity and scour depth near the permeable groynes in tests T2, T6 and T8

6.2.5 Conclusion

A permeable groyne can be an effective bank protection measure because it can reduce the flow velocity along the bank without creating big eddies and back currents.

A falling apron of dumped blocks around the piles of a permeable groyne can be an effective protection against the development of scour holes under moderate hydraulic conditions and a water depth of 10 m only. Under these moderate hydraulic conditions maximum scour depths of 1 to 3 m are expected. These depths confirm the results of the previous model tests in RRI in which a maximum scour depth of 6 to 8 m was measured near the same groyne but in a water depth of 16 m. The tendency is that as the water depth increases also the scour depth will increase.

Although in practice the percentage of blockage by floating debris may be greater than tested it is expected that floating debris does not create a problem for a permeable groyne with a falling apron under the moderate hydraulic conditions with a water depth of 10 m.

6.3 Impermeable Groyne

6.3.1 Introduction

From the first series of tests with permeable groynes, T1 to T5, it appeared difficult to study the behaviour of falling aprons because this type of structure does not generate a sufficient deep scour hole. It was planned to replace the permeable groynes by impermeable vertical plates in the next series of tests, because an impermeable groyne can create a deep scour hole. The impermeable groynes were constructed with a vertical plate placed at the upstream side of the permeable groynes.

In total 4 tests were carried out with an impermeable groyne: T7, T9, T10, T11. The tests T7, T9, T10 were run with the same hydraulic parameters while the discharge was strongly increased in T11 to have an impression of the sensitivity of the test results for an increase of the flow velocities. The prototype water depth was constant 10 m in these tests, but the length scale varied between 15 and 25. The length of the groynes was 60 m. In each test the groynes were protected by a falling apron of cc-blocks of 4x4x4 cm. These blocks were dumped in shallow stagnant water before the start of the test, see Table 6.3-1.

In this section the tests under a moderate hydraulic conditions are analyzed in Subsection 6.3.2, Test T11 in Subsection 6.3.3 and the comparison between tests with permeable and impermeable groynes is presented in Subsection 6.3.4. The conclusions of the tests with impermeable groynes are summarized in Subsection 6.3.5.

Test No.	Length scale of model	Type of groyne		Width falling apron (m)		Placing	Layer thickness	Size of blocks used
				u/s of groyne	d/s of groyne	u/s gr.	u/s gr.	u/s gr. (cm)
T7	15	u/s 1 d/s 2	Imp Imp	10 -	15 -	dumped -	2 -	4x4x4 -
T9	15	u/s 1 d/s 2	imp imp	5 -	7 -	dumped -	1 -	4x4x4 -
T10	25	u/s 1 d/s 2	- imp	- 8	- 8	- dumped	- 1	- 4x4x4
T11	25	u/s 1 d/s 2	- imp	- 8	- 8	- dumped	- 1	- 4x4x4

Table 6.3-1: Falling apron placed around the impermeable groynes

6.3.2 Moderate Hydraulic Conditions

In the 3 tests T7, T9 and T10, the water depth was 10 m and the cross-section averaged flow velocity varied between 2.0 m/s and 2.5 m/s. In tests T7 and T9 the length scale was 15 and in T10 it was 25. The results of the tests can be divided in flow velocities and flow pattern and the scour. These aspects are discussed separately.

(i) Flow Velocities and Flow Pattern
The impermeable groyne deflected the flow towards the center of the channel. A flow line separated the deflected flow from a low-velocity back-current. Strong vortices formed from the head of the groyne along this separating flow line. This vortex street generated scour of the sand bed. The eroded sand deposited partly in the downstream part of the model, partly it left the model.

The downstream groynes in T7 and T9 were not far enough from the upstream one to be attacked again by the main current. In a straight channel the spacing of 250 m could probably be increased with groynes having an orientation of 15° to the flow direction. Therefore the analysis of the results of T7 and T9 will focus on the results of the upstream groyne along the left bank.

In these tests the flow velocity field in the vicinity of the impermeable groyne was similar. Under the same conditions the maximum flow velocity near the head of the groyne reproduced rather well in T7 and in T9.

Test	Length of groyne	Cross-section averaged flow velocity	Maximum depth averaged flow velocity near the head of the groyne
(-)	(m)	(m/s)	(m/s)
T7	60	2.2	2.5 to 2.6
T9	60	2.0 to 2.4	2.2 to 2.6
T10	60	2.8 to 2.9	3.0 to 3.3
T11	60	4.2 to 4.5	3.7 to 4.7

Table 6.3-2: The maximum flow velocities near an impermeable groyne in various tests

(ii) Scour

The scour pattern in the three tests T7, T9, and T10, can be seen on the photographs in annexes T7B, T9B and T10B. During those tests an important scour hole developed downstream of the groyne. These scour holes reached their equilibrium size after running the model for 8 to 10 hours. From that time to the end of the test after 20 hours, the scour hole in T7 and T9 did not change significantly.

The maximum scour depth varied between 8.7 and 10.5 m in those three tests, because of different falling aprons. By comparing T9 and T10 with an almost identical falling apron it is seen that the maximum scour depths of 10.1 and 10.5 m respectively are almost the same.

(iii) Falling apron

A falling apron should reduce the scour of the river bed in the direct vicinity of the impermeable groyne to safeguard the stability of the impermeable groyne. The main parameters of a falling apron are the width and the thickness of the apron and the size of the cc-blocks.

- The width of a falling apron

From the results in Table 6.3-3 which are also presented in Figure 6.3-1 it is seen that an increase in the width of the falling apron made of cc-blocks:

- o reduced the maximum scour depth;
- o reduced the steepness of the side slope of the scour hole, and
- o increased the distance between the head of the impermeable groyne and the location of the point with the maximum scour depth.

These tendencies can be explained from the flow pattern and the dissipation of the turbulent energy. The width of a falling apron seems to be an important parameter to control the size of a scour hole.

The steep side slope of 1 in 1.1 is probably close to the angle of repose of the river bed material. This means a high risk of soil mechanical instability. Therefore a width of 7 or 8 m is considered to be too small and a 15 m width is a minimum width for such an impermeable groyne.

- The Thickness of a Falling Apron

Near the head of the groyne it was observed that a part of the side slope of the scour hole was not protected by the blocks of the falling apron. This side slope affected the movement of the blocks, creating a gap in the distribution of the blocks over the slope. The top of the slope was protected by the stable blocks while those which were displaced did not stay on the slope but fell down on the toe of the slope. If the flow direction changed with time, this unprotected portion of the slope could be attacked by the main flow and could not prevent a further development of the scour hole very close to the head of the groyne. Therefore a complete covering of the scour hole with cc-blocks near the head of the groyne is required. This result depends on the apron thickness of the falling apron which was only 1 to 2 layers of cc-blocks in those tests.

In T7 the falling apron prevented the development of a scour hole at the upstream side of the groyne. In T9, the quantity of blocks laying in front of the head of the groyne did not stop the scour process and the head of the groyne itself was attacked. In T7 about 4 times more blocks than in T9 were disposed over a two times longer stretch.

It is concluded that a layer thickness of 1 or 2 blocks near the head of such an impermeable groyne is insufficient. A minimum layer thickness of 3 blocks is recommended.

- Block Size

In the 3 tests with impermeable groynes, blocks of 4x4x4 cm (model value) were systematically used for the falling apron. But, because of the different scale in T9 and in T10, the small blocks are representing prototype blocks of 60 cm in T9 and prototype blocks of 100 cm in T10. Comparing the results of T9 and T10 it seems that the size of the blocks has not a prominent part in the behaviour of the falling apron when the blocks have a sufficient weight to resist the flow attack.

Test	width	thickness	maximum scour depth	distance of max. scour depth to the head of groyne	maximum side slope of the scour hole
(-)	(m)	(layers)	(m)	(m)	(-)
T7	15	2	8.7	42	1: 1.8
T9	7	1	10.5	26	1: 1.5
T10	8	1	10.1	22 to 30	1: 1.1
T11	8	1	16.2	41 to 50	1: 1.1

Table 6.3-3: The characteristic parameters of the scour hole and of the falling apron near an impermeable groyne

6.3.3 Effect of the Model Discharge

The ten first tests were run with a model discharge corresponding to the 1 in 2 years flood and a water depth of 10 m. In test T11 the model discharge was increased to investigate the sensitivity of the model results for an increase of the discharge by comparing the results of T11 with the results of T10. The results of the model regarding flow velocities and flow pattern and scouring are discussed separately.

(i) Flow Velocities and Flow Pattern

T10 and T11 reproduced exactly the same situation at a scale 1 in 25. The cross-section averaged flow velocity was increased about 50 % from 2.8 to 2.9 m/s in T10 to 4.2 to 4.5 m/s in T11. The increase in the maximum flow velocities near the head of the groyne was 20 to 40 %: from 3.0 to 3.3 m/s in T10 to 3.7 to 4.7 m/s in T11. In the measured flow pattern around the head of the groyne relatively strong flow velocity gradients might occur because of the high turbulence intensity and a relatively short measuring time of the flow velocity. The comparison of T10 and T11 shows that the qualitative flow velocity distribution and the flow pattern were not influenced by the increase of the model discharge, but the turbulence intensity near the groyne was increased in T11.

(ii) Scour

The bed erosion around the groynes can be seen on the photographs of the annexes T10B and T11B. The contour lines of the scour holes in both tests are sketched in annexes T10E and T11E.

Comparing test T11 with test T10 it is seen that the maximum scour depth has been increased considerably from 10.1 m to 16.2 m and that the location of the maximum scour was shifted 20 to 30 m in downstream direction. The gradient in the bed level near the deepest point of the scour hole was small in the main direction of the flow. Therefore a shift in downstream direction does not necessarily mean big changes in the geometry of the scour hole.

An increase of 60 % in the scour depth was caused by a flow velocity increase of about 50%. This means that the maximum scour depth is rather sensitive for an increase of the model discharge.

At the upstream side of the scour hole the gradients became smaller in T11 (compared with T10) and also the scour hole extended further upstream relative to the groyne head. In a prototype one should expect a scour hole with a layout at its upstream side as measured in T11.

(iii) Falling Apron

The falling apron behaviour did not change because of an increase of the flow velocities which did not entail the displacement of the blocks of the apron. They slided, creeped down the slope of the scour hole up to the deepest point of the scour hole in a similar way in both tests. The deeper scour hole in T11 caused a larger area unprotected by the blocks just downstream of the head of the groyne as in test T10. At the upstream the coverage of the bed by one layer of blocks was quite good in both tests, but from the sketches with the contour lines it can be seen that a single layer does not provide an effective protection. In the area of the falling apron the contour lines are not disturbed to follow the original bed level, what should be expected if the falling apron gives an effective protection.

A possible scale effect in creeping and sliding of the blocks caused the blocks to slide and to creep too easily in the model. In prototype the blocks will not slide that far as in the model. It is concluded that a single layer of blocks is not sufficient for an effective falling apron.

6.3.4 Comparison with the Tests of a Permeable Groyne

In T11, a permeable groyne was placed on the right bank and an impermeable groyne on the left bank. All the parameters were equal for both the groynes.

After completion of the test the scour holes created by the two types of groynes were very different. The maximum scour depth around the permeable groyne was 4 to 5 times less than the scour around the impermeable one. The maximum scour depth of 3.7 m near the permeable groyne and 16.2 m downstream the vertical wall of the impermeable groyne. This confirms the results of the previous investigations in RRI.

6.3.5 Conclusion

A vertical plate acting as an impermeable groyne generated a deep local scour hole in the river bed. These holes had rather steep slopes close to the angle of repose of the river sand. The slope was so steep that a single layer of blocks could not stay on the slope and guarantee the toe protection.

The maximum scour depth is rather sensitive for an increase of the model discharge.

A width of 7 or 8 m is considered to be too small for a falling apron to guarantee soil mechanical stability. The tested impermeable groyne should have a falling apron with a minimum width of 15 m. A falling apron with a layer thickness of 1 or 2 blocks near the head of such an impermeable groyne seems to be insufficient. A falling apron with a minimum layer thickness of 3 blocks is recommended. It seems that the size of the blocks does not influence the behaviour of the falling apron when the blocks have a sufficient weight to resist the flow attack.

6.4 Cross-bar

6.4.1 Introduction

In the preliminary design of the test structure with groynes two cross-bars were included to prevent an embayment just downstream of the series of groynes. These cross-bars were intended to be built on the flood plain and only the head of the cross-bar protrudes into the river. The behaviour of a falling apron around the head of the cross-bar was studied in four tests: one test without a falling apron as a reference case (Subsection 6.4.2) and three tests with a different layout of a falling apron of cc-blocks (Subsection 6.4.3).

In all tests moderate hydraulic conditions and a water depth of 15 m were simulated. The water depth was increased compared with the previous tests, because the length scale of the model was increased from 15 to 25. This scale was selected because the previous tests had shown no systematic differences between the results of tests on a length scale 15 and tests on a length scale 25 and, also, it allowed to build two structures (a revetment and a cross-bar) in the model. The distance between these structures was sufficient to avoid influences on each other. The analysis of these tests is focused on the efficiency of a falling apron to reduce the scour hole downstream of the cross-bar. An optimized layout of a falling apron around the head of a cross-bar is presented in Subsection 6.4.4.

6.4.2 Cross-bar without Bed Protection

A cross-bar without a falling apron was tested in T12. The protecting top layer of the head of the cross-bar was simulated in the model as a rigid concrete cover layer. The slope of this protecting top layer was 1 in 3 from the top to the bottom. The toe of this cover layer was on the initial bed level, see Appendix 1.

The results of the test regarding flow velocities, flow pattern and scour are discussed separately.

(i) Flow Velocities and Flow Pattern

A cross-bar generated a flow diversion towards the center of the river and created downstream a separating flow line between the main flow and a back current. Along this line a strong vortex street developed from the head of the cross-bar.

The approach flow velocity increased from 2.7 m/s to a maximum flow velocity of 3.7 m/s near the head of the cross-bar, see Table 6.4-1. Along the vortex-street this high flow velocity was measured up to 90 m downstream of the head of the cross-bar.

Downstream of the cross-bar a back current with a maximum flow velocity of 1.6 m/s attacked the bank. The return flow was strong compared to the flow velocity along the bank without any structure (around 2.7 m/s).

Test	Model discharge	Cross-section averaged approach flow velocity	Maximum flow velocity near cross-bar
-	m^3/s	m/s	m/s
T12	5.8	2.7	3.7
T13	5.8	2.7	4.0
T14	5.7	2.6	4.1 / 4.0
T15	5.8	2.7	4.5

Table 6.4-1: Model discharge and characteristic flow velocities in T12 to T15

(ii) Scour
Downstream of the cross-bar a scour hole developed with a maximum depth of 14.4 m, see Table 6.4-2. The scour hole had a length of about 130 m and a width of about 65 m. The slope of its sides were varying from 1:2 to 1:4.

After running the test for 6 hours the scour hole became in equilibrium. Some sand was eroded under the concrete cover layer of the cross-bar as the scouring progressed. In the prototype a cross-bar without any toe protection can be severely damaged by the erosion under extreme hydraulic conditions.

Downstream of the cross-bar in between the vortex street and the bank, a deposition of sand was observed. The back current mentioned previously flowed between this deposition and the bank, which will probably erode and some embayment will develop. This deposition and bank erosion were not simulated on scale in the model because of scale effects.

Test	Width falling apron	Layer thickness falling apron	Maximum scour depth	Location maximum scour depth
-	m	block size-	m	m
T12	0	0	14.4	75, 47
T13	7.5 to 15	2	10.4	94, 66
T14	5 to 22	2/3	11.8	112, 56
T15	10 to 15	2/3/4	11.4	75, 47

Table 6.4-2: Size of falling apron and scour hole in T12 to T15

6.4.3 Cross-bar with a Falling Apron

The head of the cross-bar was protected in T13 to T15 by a falling apron of cc-blocks dumped in shallow stagnant water. The purpose of these tests was to optimize the layout of the falling apron around a cross-bar. The results of these tests regarding flow velocities and flow pattern, scour and some aspects of the falling apron are discussed separately.

(i) Flow Velocities and Flow Pattern
The flow pattern was similar in those 3 tests with a vortex street starting from the head of the cross-bar towards the river and downstream of the cross-bar a strong eddy with a back current along the bank was generated by the cross-bar.

The maximum flow velocity in the test with a falling apron (4.0 to 4.5 m/s) was higher than the maximum flow velocity in the test without a falling apron (3.7 m/s), see Table 6.4-1. A falling apron enforced the rigid part of the cross-bar which blocked the approach flow. Therefore a falling apron results in a stronger deflection of the flow and higher flow velocities. An increasing width of the falling apron causes higher maximum flow velocities, see Figure 6.4-1. Therefore the width of the falling apron should be as small as possible.

(ii) Scour

Basically the scour pattern was similar in those tests. The maximum scour depth varied between 10.4 and 11.4 m what is less than 14.4 m in T12 without a falling apron, see Table 6.4-2. A falling apron reduced the maximum scour depth with a few meters, but a falling apron caused also the location of the maximum scour depth to shift 20 to 30 m from the head of the cross-bar, see Figure 6.4-1. These are direct positive effects of the falling apron.

An indirect effect is the coverage of the upstream side of the local scour hole. In T13 a layer thickness of 2 blocks was not sufficient for a complete coverage. This was improved by increasing this thickness to 3 and 4 layers.

Compared to test T12, the falling apron prevented the erosion of sand under the concrete cover layer of the cross-bar.

(iii) Falling apron

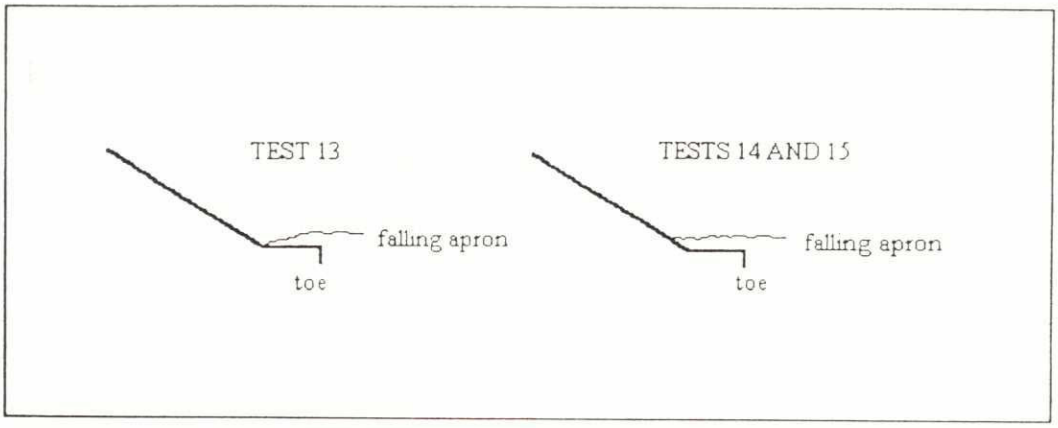
Some remarks on the placement of the blocks, the layer thickness and on the behaviour of a falling apron are presented here as additional background information. The size and the layer thickness of the falling apron were varied in T13 to T15. These changes did not affect the general layout of the scour hole but they had an effect on the toe protection.

- Placement of the blocks:
  The cc-blocks were dumped from the water surface in shallow stagnant water. The process was easier than in prototype because the bed was visible through the water which helped to place the blocks in the foreseen area. In prototype, an accurate positioning system to dump cc-blocks precisely at the designed locations will probably need some attention.

- Total number of blocks:
  The number of blocks was defined by the area and the thickness of the falling apron around the cross-bar. The total volume of the falling apron was calculated by multiplying this area by the layer thickness. To determine the number of blocks, the porosity of the dumped cc-blocks was determined at 30 to 35%.

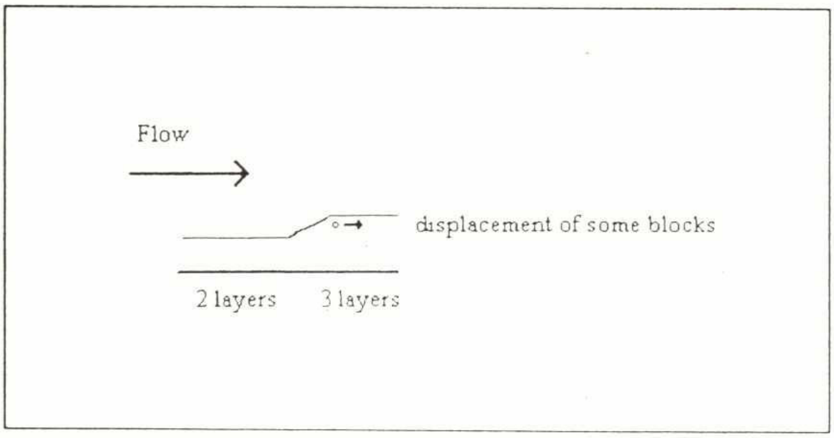
- Behaviour of the blocks:
  Before the start of the test, the falling apron was laid on an horizontal channel bed. The model was started by slowly filling it and the flow velocity increased within a few minutes to the required values. Downstream of the cross-bar, the scour process started quickly. The scour hole began to form and the blocks at the extremity of the falling apron started to slide and creep and to cover the slope of the beginning scour hole.

  The blocks fell down and started to cover the upstream side of the scour slope. The average slope was 1:2, see Figure 6.4-2. The toe of the cross-bar was visible in some places in T13 because the number of blocks placed on the berm where not sufficient, see the sketch below. In T14 and T15, the toe of the structure was well protected and did not appear in any places around the cross-bar.Therefore it is recommended to have an overlap of the toe of a rigid protecting cover layer and the falling apron over a width of at least 2.5 m or 5 B (B = block size) and without a reduction of the thickness of the falling apron. If this protecting cover layer has some flexibility, than this overlap is not required.



The maximum hydraulic load on the blocks of the falling apron around the head of the cross-bar was observed near the separating flow line between the main flow and the big eddy downstream of the cross-bar. Along this flow line a vortex street developed starting from the separating point at the head of the cross-bar. The layer thickness of the falling apron should be maximum there. A lot of blocks placed there, fell down in the scour hole. As a result a part of the falling apron was eroded.

Increasing the thickness of the falling apron around the head of the cross-bar at the point of maximum hydraulic load resulted in various sections with different thicknesses. At the transition to a downstream section with a higher thickness the erosion of the blocks will start first, as was observed in T15 where the thickness was increased from 2 to 4 layers, see sketch below. This phenomenon was not observed in T13 and T14 where the thickness of the falling apron was less.



An incomplete coverage of the upstream side of the scour hole near the head of the cross-bar gives not sufficient protection and in principle it can be improved by two measures:

(1) **To increase the width of the falling apron and keeping the layer thickness constant:**
This measure causes mainly a shift of the scour hole away from the head of the cross-bar, but it did not improve the incomplete coverage of the upstream side of the scour hole. This can be noticed on the photographs of tests T13 and T14, see annexes T13F, T14D and T14E.

(2) **To increase the layer thickness of the falling apron and keeping the width constant:**
This measure improves the coverage of the upstream side of the scour hole with cc-blocks, but it did not shift the local scour away from the head of the cross-bar. This can be confirmed by the photographs of both T13 and T15, see annexes T13F and T15D.

In general measure 2 is recommended as a safe and efficient measure resulting in relatively short and thick falling aprons around a cross-bar.

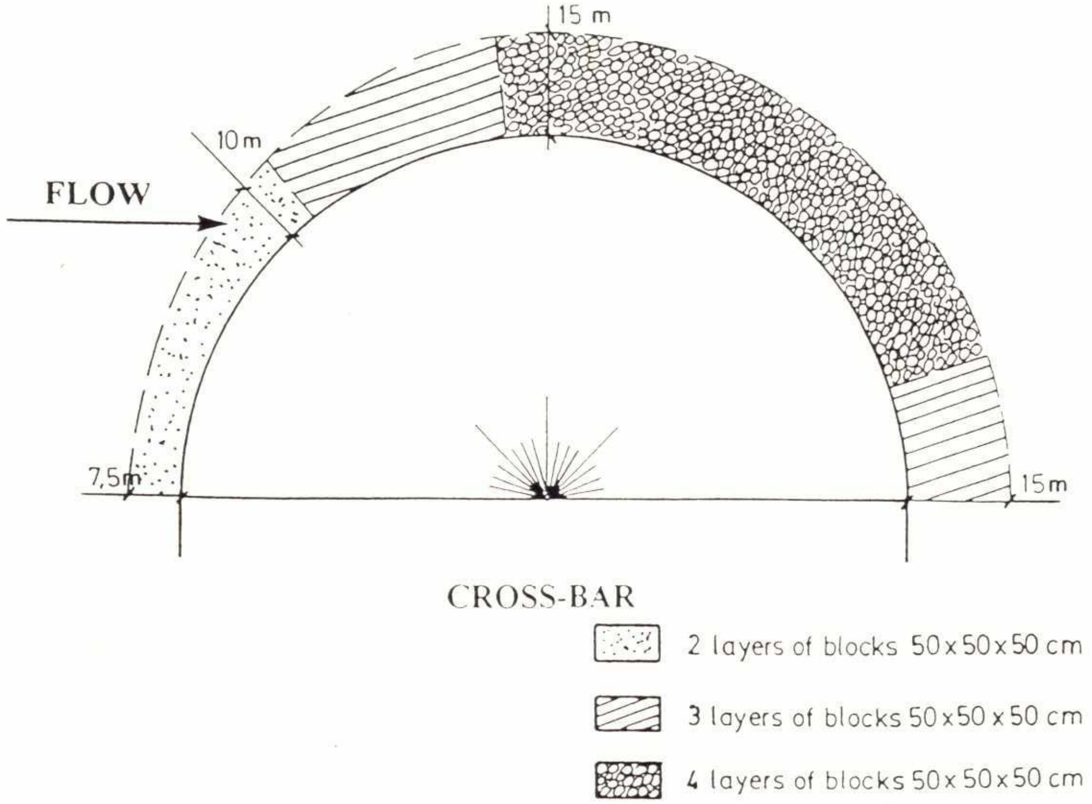
6.4.4 Layout of Falling Apron around a Cross-bar

An optimized layout of a falling apron around the head of a cross-bar was made on the basis of the results of T12 to T15. This means that this layout does not include possible effects of bank erosion upstream of the cross-bar. Also the direction of the approach flow is not varied and it is assumed to be parallel to the initial bank line. The river bed is assumed to be horizontal and flat with a steep side slope near the bank in this investigation and therefore major deviations in the bed level of the river may require adjustments in the design of the falling apron.

(i) Falling Apron Layout
The falling apron around the head of a cross-bar should be divided in several sections. A minimum width in the sections with less flow attack is recommended at the upstream side of the head of the cross-bar and the width should gradually increase to a maximum width near the separating flow line. Possible shifts in this separating flow line should be investigated carefully or a sufficient wide range of this section with maximum width should be selected.

Further downstream it is recommended not to reduce the maximum width although the hydraulic load will probably be less. The presented values in the sketch below are tentative only. It is recommended to have an overlap of the toe of a rigid protecting cover layer and a falling apron over a width of at least 2.5 m or 5 B. If the protecting layer has some flexibility than this overlap is not required.

(ii) Layer Thickness
A minimum layer thickness of the falling apron of about 2 B is recommended in the sections with less flow attack at the upstream side of the head of the cross-bar and this thickness should gradually increase to a maximum layer thickness of about 4 B near the separating flow line, see the sketch below. In general a falling apron should have a minimum thickness of 2 block sizes where no high flow velocities are expected. The transition from one layer thickness to a section with an increased thickness should be smooth. To determine the number of blocks the porosity of the dumped cc-blocks is estimated at 30 to 35 %. The size of the blocks is determined by stability formulas for flow attack with a high turbulence level in the vortex street or by the stability formulas for wave attack.



6.5 Revetment

6.5.1 Introduction

In the preliminary design of the test structure with a revetment, the alignment of the revetment was more or less parallel to the main flow direction and the initial bank line. Because of continued bank erosion upstream of the revetment and possible variations in the approach flow the revetment can become more exposed to flow attack and the revetment needs protection by a falling apron.

The behaviour of a falling apron around a revetment was studied in four tests: one test without a falling apron as a reference case and three tests with a different layout of a falling apron of cc-blocks. In all those tests moderate hydraulic conditions were simulated and the water depth was kept constant at 15 m. The upstream bank was assumed to be eroded over a width of about 100 m and the alignment was parallel to the main flow direction of the approach flow, to simulate a moderate flow attack on an exposed revetment.

The analysis of these tests is focused on the efficiency of a falling apron to reduce the scour hole near the upstream termination of the revetment (Subsection 6.5.2). An optimized layout of the falling apron around a revetment is presented in Subsection 6.5.3.

6.5.2 Efficiency of a Falling Apron

The protection layers of the revetment were simulated in the model by a rigid cemented layer. The toe of these layers is designed above a minimum water level, which is around standard low water. In T12 this toe was not protected by a falling apron as a reference case for the tests with different falling aprons under the same hydraulic conditions in T13 to T15, see for details of these tests Appendix 1. The slope of the protection layers of the revetment was 1 in 3. Its toe laid on the initial horizontal bed. The upstream termination of the revetment had a radius of 50 m. The falling apron consisted of a layer of cc-blocks, dumped in stagnant water before the start of the test. The results of this test regarding flow velocities, flow pattern and scour are discussed separately.

(i) Flow Velocities and Flow Pattern
The revetment protruded about 100 m in the river and in this position the revetment caused a deflection of the approach flow towards the center of the channel. The flow could not follow the short radius of the upstream termination of the revetment. An eddy with a vortex street along the separating flow line near the transition between the straight section of the revetment and the upstream termination could be observed. The flow velocities in this eddy were lower than those in the eddy generated by the cross-bar. This general flow pattern was similar in all the tests T12 to T15.

The flow accelerated from 2.7 m/s upstream of the structure to 3.5 m/s along the revetment. A falling apron did increase the maximum flow velocity near the revetment with 0 to 0.4 m/s. This tendency had also been observed near the cross-bar where this increase ranged from 0.3 to 0.8 m/s, see Table 6.5.1.

Test	Cross-section averaged approach flow velocity	Maximum flow velocity approach near cross-bar	Maximum flow velocity near revetment
-	m/s	m/s	m/s
T12	2.7	3.7	3.5
T13	2.7	4.0	3.7 to 3.8
T14	2.6	4.1 / 4.0	3.9
T15	2.7	4.5	3.5 to 3.6

Table 6.5-1: Average and maximum flow velocities in T12 to T15

(ii) Scour
Along the toe of the rigid cover layer without adjacent falling apron the scouring developed close to this toe with a maximum scour depth of 7.4 m measured at the end of the upstream circular termination. The hole had a length of about 140 m and a width of about 60 m and a gentle side slope 1:5, see Table 6.5-2. However, this maximum scour depth was reduced by the presence of stiff clay particles of gravel size. Therefore it is expected that the maximum scour depth in clean sand would have been more than 7.4 m, maybe 8 to 9 m.

A maximum flow velocity of 3.7 m/s washed away the falling apron of cc-blocks 0.25x0.25x0.25 m downstream of the upstream termination over a length of some 50 meters. Therefore in the next test the size of the blocks was increased to 0.5x0.5x0.5 m, resulting in a sufficient stable falling apron. Only the coverage of the slope of the scour hole was not sufficient: 0.5 to 1.5 blocks per m^2 on the lower part of side slope of the scour hole. For a good coverage about 3 blocks 0.5 x0.5x0.5 m per square meter are required. Therefore the layer thickness was increased from 2 to 3.5 blocks increasing the number of blocks per running meter falling apron from 50 - 56 to 82 - 86. However, even after this increase not a sufficient coverage of the slope could be obtained with 0.5 to 1.5 blocks per m^2, partly because of a scale effect in the movement of the blocks, partly because the test duration was 10 hours only. In practice the coverage will be slightly higher as observed in the model. The width of the falling apron was kept constant at 7.5 m or about 1 * y_s in those tests where y_s is the maximum scour depth.

A stable falling apron in T14 and T15 reduced the maximum scour depth from 7.4 m (or 8 to 9 m) to 5.0 m and shifted the place of the maximum scour depth about 7.5 m from the revetment. This shift is equal to the width of the falling apron. But the maximum side slope of the scour hole increased from 1:5 to 1:2 with a good falling apron, see Figure 6.4-2. The blocks fell in the scour hole along a slope 1:2. The coloured blocks disposed on several places proved that the blocks did not move downstream in the flow direction because after the tests they were found in the same perpendicular line to the revetment as before the test.

Test	Width falling apron	CC-block size	Layer thickness falling apron	Maximum scour depth	Location of maximum scour depth	Maximum side slope of the scour hole
-	m	m u/s / d/s	block size- u/s / d/s	m	(see local grid in Annexes)	(see local grid in Annexes)
T12		0/0	0/0	7.4	0, 10	1:5
T13	7.5	0.25/0.25	3.5/3.5	7.6	37.5, 10	1:5
T14	3.75 to 7.5	0.50/0.25	2.0/3.5	5.5	37.5, 18.75	-
T15	7.5	0.50/0.50	3.5/2.0	5.0	37.5, 18.75	1:2

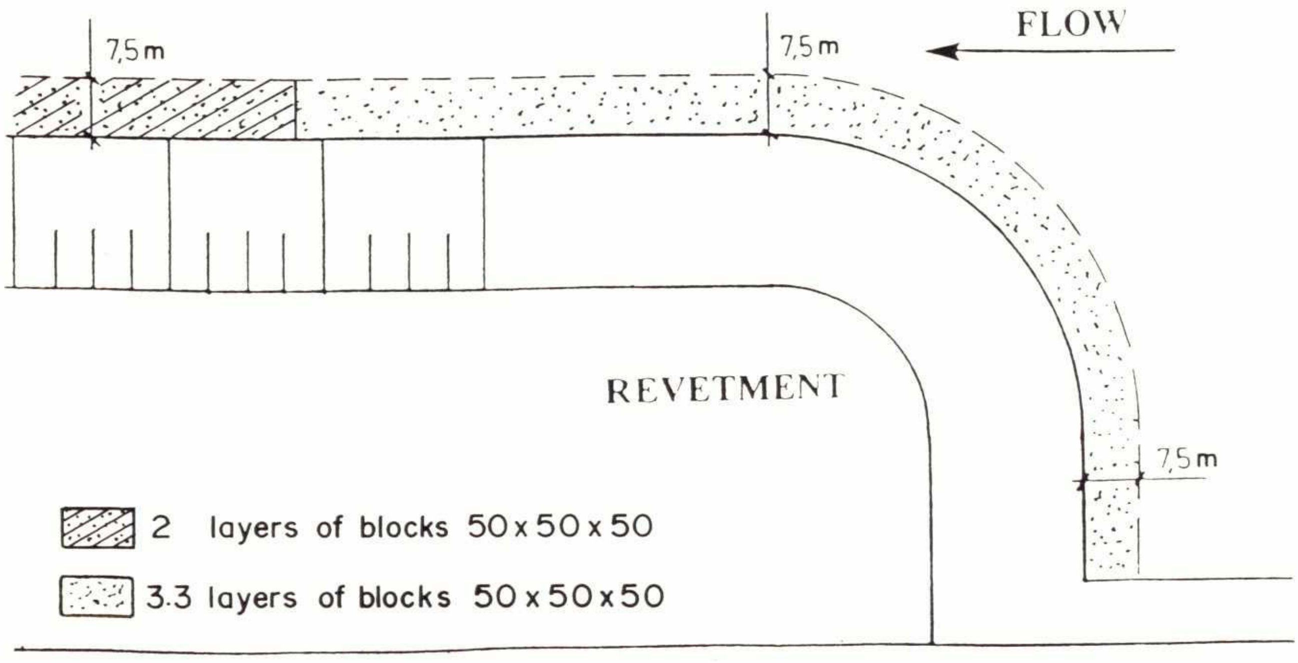
Table 6.5-2: Size of falling apron and scour hole in T12 to T15

6.5.3 Layout of Falling Apron around a Revetment

An optimized layout of a falling apron around the revetment was made on the basis of the results of T12 to T15. This means that this layout did not include possible effects of continued bank erosion upstream of the revetment. Also the direction of the approach flow was not varied and it was assumed to be parallel to the initial bank line. The river bed was assumed to be horizontal and flat with a steep side slope near the bank in this investigation and therefore major deviations in the bed level of the river may require adjustments in the design of the falling apron of the test structure.

(i) Falling Apron Layout
A minimum width of 7.5 m is recommended for the whole revetment. The presented values in the sketch below are tentative only. It is recommended to have an overlap of a rigid protecting cover layer and the falling apron at the toe of the protecting cover layer over a width of at least 2.5 m or 5 B and without a reduction of the thickness of the falling apron in the overlapping zone. If the radius of the upstream termination is increased then the same design rules for a falling apron can be applied. The falling apron around the downstream termination should be designed as the falling apron around the upstream termination, because the vortex street along the separating flow line will cause also a local scour hole near the downstream termination of the revetment.

(ii) Layer Thickness
The falling apron around the revetment should be divided in three sections: one section covering the upstream termination and 50 m revetment, a mid-section with the straight revetment and a section with the downstream termination. A minimum layer thickness of the falling apron of about 3.3 B is recommended in the upstream section with a strong flow attack at the upstream termination and this thickness can be reduced to 2 B in the downstream section, see the sketch below. In general a falling apron should have a minimum thickness of 2 block sizes. To determine the number of blocks the porosity of the dumped cc-blocks is estimated at 30 to 35 %. The size of the blocks is determined by the stability formulas for flow attack with a high turbulence level and near the water level by the stability formulas for wave attack.



6.6 Design of Falling Aprons

The integration of the analysis of the falling apron behaviour near groynes, a revetment and a cross-bar has resulted in a recommended design method for falling aprons made of dumped blocks. This method is described in this section and a comparison with other methods is included.

6.6.1 Design Method

In this design method the value of two parameters should be known. One of these parameters is the maximum flow velocity near the toe of the protection. This maximum flow velocity determines the size of the cc-blocks of the falling apron, because each individual block should be stable under the design flow attack.

Another given parameter is the maximum scour depth under design conditions y_s. If the falling apron is dumped on a natural slope then y_S is the maximum vertical depth over which the falling apron is supposed to fall. In that case y_S can be smaller than the maximum scour depth.

The volume V of the falling apron per meter more or less parallel to the main flow direction is:

$$V = c_1 * y_s * B \qquad \textbf{(6.1)}$$

in which

B	=	block size	(m)
c_1	=	coefficient	(-)

It is recommended to use $c_1 = 4$ for a moderate flow attack and 5 for a strong flow attack, see Figure 6.6-1. The background for these values is:
for moderate flow attack:

$$V = 0.5 * y_s * 1.5 * B + y_s * 3.3 * B \qquad \textbf{(6.2)}$$

for extreme flow attack:

$$V = 1.5 * y_s * 3.3 * B \qquad \textbf{(6.3)}$$

The thickness of the falling apron, T_{apron}, is 3.3 cc-blocks near the head of the falling apron and to obtain a sufficient coverage of the side slope of the scour hole. If the flow attack is moderate then the thickness can be reduced to 1.5 B over 0.33 W near the transition to the fixed protection layer with W = width of the falling apron. Those blocks are not supposed to fall or creep but are supposed to remain stable to guarantee a full protection of the transition to the protection layer, see the measured final position of the falling apron in the physical model tests in Figure 6.6-2. The overlap of 2.5 m or 5 B is only required if the cover layer is very rigid, without any flexibility.

The width of the falling apron is

$$W = V/T_{apron} = 1.5 * y_S \qquad \textbf{(6.4)}$$

in which

T_{apron} = thickness of the falling apron

The background is that the final position of the falling apron is characterized by a slope 1:2 and a layer thickness of 1.5 blocks.

To estimate the number of blocks required for the falling apron a porosity of 30 to 35 % can be assumed.

With these expressions for the volume, width and thickness of a falling apron the geometry of a falling apron can be determined. These expressions should be used as general guidelines for the design of a falling apron. For each type of hydraulic structure as cross-bar or a revetment additional design rules for a falling apron should be used as discussed in the previous chapters.

6.6.2 Comparison with other Methods

In the Final Report of the Planning Study, Section 7.4.6 of the main report, a review of the existing design methods of toe protections is given with special emphasis on falling aprons.

The comparison of the FAP 21 design method with the various other methods, as presented in Table 6.6-1 shows that the design methods of FAP 1 for hard points in the Jamuna river and of FAP 9B for the protection of Chandpur result in 20 % to 30 % more blocks per meter than in the proposed FAP 21 design. It is mentioned that the river training works designed by FAP 9 B and FAP 1 were relatively large structures exposed to a strong flow attack. But in comparison with the other methods FAP 21 has an increased thickness and an average width of the apron resulting in an increased volume per meter length. It is remarkable that the variation in the width in most methods is rather small: the average width is 1.5 y_s with a minimum 1.25 y_s and a maximum of 1.8 y_s.

Source/Author	c_1	Width	Thickness
BWDB	1.8	$1.8 \cdot y_s^{0.5}$	1.0 . B
Gales	2.25	$1.5 \cdot y_s$	1.5 . B
Hemphill/Bramley	2.5	$1.7 \cdot y_s$	1.5 . B
Spring, Rao	2.82	$1.5 \cdot y_s$	1.9 . B
FAP 1 strong attack moderate attack	6.75 5.25	$1.5 \cdot y_s$ $1.5 \cdot y_s$	4.5 . B 3.5 . B
FAP 9 B	5.9	$1.25 \cdot y_s$	4.7 . B
FAP 21 strong attack moderate attack	5.0 4.0	$1.5 \cdot y_s$ $1.5 \cdot y_s$	3.3 . B 2.7 . B

Table 6.6-1: Comparison of the main parameters of a falling apron in different methods

6.7 Dumping Method

In most of the tests the cc-blocks of the falling apron were dumped from the water level in stagnant shallow water before the start of a test. Since the construction of the test structure is planned in the lean season with low flow velocities in the Jamuna river, the dumping of the blocks is comparable with the dumping of the blocks in the model. However, if during the monitoring period a need for an emergency repair is identified under high flood conditions then during their fall the blocks might be moved by the flow over a considerable distance before reaching the river bed. A good position system will be required for such an repair.

In two additional tests the dumping of blocks in a high flow velocity was investigated. The first test was an estimation of the displacement of blocks of different size dumped in a flow of 3.5 m/s to determine the distance between the dumping place and the location where the falling blocks reach the river bed. The second one was a trial to improve the protection of the cross-bar by dumping blocks in high flow velocity conditions.

(i) First Test

Two series of 10 blocks of 0.02, 0.03 and 0.04 m size (model value) were dumped in the flow from the water surface and from 10 m above the water surface. The water depth was 15 m and the mean flow velocity was 3.5 m/s at half the water depth. The blocks fell down downstream of their point of dumping. Of course, they fell as further if their weight was less, but the scattering in these distances was considerable, see Table 6.7-1 and Figure 6.7-1.

Falling depth	Block size	F_D / F_g	Falling distance		
			Minimum	Mean	Maximum
m	m^3	-	m	m	m
15 + 10	0.50	1.5	10.5	15.8	22.6
	0.75	1.0	9.9	13.3	18.0
	1.00	0.75	7.8	10.3	13.1
15	0.50	1.5	9.3	12.0	15.4
	0.75	1.0	8.3	8.5	8.8
	1.00	0.75	3.8	6.0	9.1

Table 6.7-1: Distance between place of falling above the water level and place of reaching the river bed in high flow velocities

The distance between place of falling above the water level and place of reaching the river bed in a flow depends on the ratio between the drag force exerted by the flow on the blocks and the weight force of the blocks. This ratio is given in the following formulas.

$$F_D = C_D * A^2 * \frac{1}{2} \rho * u^2 \qquad (6.5)$$

$$F_g = (\rho_s - \rho) * g * B^3 \qquad (6.6)$$

$$\frac{F_D}{F_g} = \frac{1}{2} * \frac{C_D * u^2}{g * \Delta * D} \qquad (6.7)$$

in which

A	=	Area of the block perpendicular to the approach flow direction	m^2
C_D	=	coefficient of the drag force	-
B	=	size of the block	m
F_D	=	drag force on a block	N
F_g	=	gravity force on the block	N
g	=	acceleration by gravity	m/s^2

u	=	approach flow velocity	m/s
ρ	=	density of water	kg/m^3
ρ_s	=	density of the blocks	kg/m^3

The ratio between the drag force and the gravity force has been calculated assuming: $C_D = 2$, $g = 9.81$ m/s^2, $u = 3.5$ m/s, $\rho = 1000$ kg/m^3 and $\rho_s = 2650$ kg/m^3. The resulting ratio is presented in Table 6.7-1.

If the flow is scaled according to the Froude law, then this ratio is reproduced in the model at the same value as in the prototype. During the time that a block falls from the water level up to touching the river bed this ratio determines the distance over which a block is transported by the flow. From Figure 6.7-1 it is seen that:
- this distance is a linear function of the ratio F_D/F_g,
- this distance depends on the height above the water level from where a block falls.

From the formulas it is seen that a reduction of the flow velocity from 3.5 m/s to 2.5 m/s will reduce this distance by 50 %.

In prototype, the dumping of blocks can take place in areas where turbulence, eddies result in an irregular flow field. This can increase the scattering in the displacement of the dumped blocks.

(ii) Second Test
After the test T14, the slope of the scour hole was not well covered by the blocks. It was tried to dump more blocks from the water surface in high flow velocity. The first trial was not successful because the 2000 blocks did not go in the right place but they were carried away by the flow, and they fell in the scour hole (see annex T14I). The second trial was a success because the 1000 blocks were dumped at about 20 m upstream of the target (see annex T14I). This example shows the importance of dumping accurately blocks from the water level.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

An investigation on the behaviour of a falling apron around various hydraulic structures was performed in a diversion channel near a dam in the Rhône river in France. In total 15 tests were performed in this CNR facility from July 1993 to June 1994. The available discharge and the dimension of this diversion channel allowed to simulate a test structure in the Jamuna river at a length scale 1 in 15.

Possible scale effects were investigated in different series of tests. The conclusion is that the deviation from the ideal sediment size introduces small or moderate scale effects in a model with permeable groynes, but in a model with impermeable groynes these scale effects were neglectable. It seems that within the tested range of block sizes no scale effect is caused by the block size on the behaviour of the falling apron when the blocks have a sufficient weight to resist the flow attack.

7.2 General Guidelines for the Design of a Falling Apron

At the location of the strongest flow attack around different hydraulic structures the volume V of the falling apron per meter more or less parallel to the main flow direction, can be estimated:

$$V = c_1 * y_s * B \qquad (7.1)$$

in which

B	=	block size	(m)
c_1	=	4 for moderate flow attack, 5 for strong flow attack	(-)
y_s	=	maximum scour depth	(m)

The thickness of the falling apron is 3.3 B for a revetment and a permeable groyne and 4 B for the head of a cross-bar. The recommended width of a falling apron is 1.5 y_s. It is recommended to have an overlap of the toe of a rigid protecting cover layer and the falling apron over a width of at least 2.5 m or 5 B and with a thickness of 3.3 B if the flow attack is strong and 1.5 B if the flow attack is moderate. This reduction can be applied over 0.33 of the width of the falling apron. If the cover layer has some flexibility then this overlap is not required. The equilibrium slope of a falling apron is about 1:2, and this has been found in many previous investigations. To determine the number of blocks the porosity of the dumped cc-blocks is estimated at 30 to 35 %. The size of the blocks is determined by stability formulas for flow attack with a high turbulence level in the vortex street.

The size of the falling apron in sections with less than the maximum flow attack around a structure is described per type of structure.

7.3 Impermeable Groyne

The tested impermeable groyne shaped as a vertical plate should have a falling apron with a minimum width of 1.5 y_s and the thickness can be reduced from 3.3 B around the head of the groyne to 1.5 B along the remaining part of the groyne, where the width can be reduced to 1 y_s. The size of the falling apron is sufficient to cover the whole scour hole around this type of groyne.

If the width of the falling apron is less than about 1 y_s than the slope of the local scour hole around an impermeable groyne was so steep that a single layer of blocks could not stay on the slope and could not guarantee a sufficient protection of the toe.

7.4 Cross-Bar

An incomplete coverage of the upstream side of the scour hole near the head of the cross-bar gives not sufficient protection and in principle it can be improved by two measures:

(1) To increase the width of the falling apron and keeping the layer thickness constant. This measure causes mainly a shift of the scour hole away from the head of the cross-bar, but it did not improve the incomplete coverage of the upstream side of the scour hole.

(2) To increase the layer thickness of the falling apron and keeping the width constant. This measure improves the coverage of the upstream side of the scour hole with cc-blocks, but it did not shift the local scour away from the head of the cross-bar.

In general measure 2 is recommended as a safe and efficient measure resulting in relatively short and thick falling aprons around a cross-bar. Measure 1 is only applicable if the falling apron covers the whole scour hole as recommended for a groyne in shape of a vertical plate.

The falling apron around the head of a cross-bar should be divided in several sections. A minimum width in the sections with less flow attack is recommended at the upstream side of the head of the cross-bar and the width should gradually increase to a maximum width near the separating flow line. A minimum layer thickness of the falling apron of about 2 B and a width of 0.8 y_s is recommended at the upstream side of the head of the cross-bar. In general a falling apron should have a minimum thickness of 2 block sizes in sections where no high flow velocities are expected. The thickness should gradually increase to a maximum layer thickness of about 4 B and a width of 1.5 y_s near the separating flow line. Further downstream it is recommended not to reduce the width of 1.5 y_s only the thickness can gradually be reduced from 4 B to 2 B.

The transition from one layer thickness to a section with an increased thickness should be smooth or it becomes smooth by the river action which moves the most exposed blocks first.

7.5 Revetment

A falling apron with a minimum width of 1.5 y_s is recommended for the whole revetment. It is recommended to have an overlap of the protecting cover layer and the falling apron at the toe of the protecting cover layer over a width of at least 2.5 m or 5 B and without a reduction of the thickness of the falling apron in the overlapping zone in case of a strong flow attack. An increase of the radius of 50 m of the upstream termination will probably not change these results.

The falling apron around the revetment should be divided in a three sections: one section covering the upstream termination and 50 m revetment designed for a strong flow attack, a mid-section with the straight part of the revetment often designed for a moderate flow attack and a section covering the downstream termination.

7.6 Dumping Method

In the dumping method of the cc-blocks these blocks fall from the water level and before reaching the river bed the flow transports the blocks over a certain distance. Some test series have shown that
- this distance ranges from 5 to 20 m in a flow of 3.5 m/s and a water depth of 15 m,
- this distance is a linear function of the ratio F_D/F_g, the drag force and the weight of a blocks,
- this distance depends on the height above the water level from where a block falls.

From some formulas it is seen that a reduction of the flow velocity from 3.5 m/s to 2.5 m/s will reduce this distance by 50 %.

7.7 Scour Holes and Flow Field

Some results of the local scour holes and the flow field around groynes are summarized:

An impermeable groyne in the shape of a vertical plate generated a deep local scour hole in the river bed. These holes had rather steep slopes close to the angle of repose of the river sand.

A permeable groyne can be an effective bank protection measure because it can reduce the flow velocity along the bank without creating big eddies and back currents.

A falling apron of dumped blocks around the piles of a permeable groyne can be an effective protection against the development of scour holes under moderate hydraulic conditions. Under these conditions and a water depth of 10 m the maximum scour depths of 1 to 3 m are expected. These depths confirm the results of the previous model tests in RRI in which a maximum scour depth of 6 to 8 m was measured near the same groyne but in a water depth of 16 m. The tendency is that as the water depth increases also the scour depth will increase.

Although in practice the percentage of blockage by floating debris may be greater than tested, it is expected that floating debris does not create a problem for a permeable groyne with a falling apron under the moderate hydraulic conditions with a water depth of 10 m.

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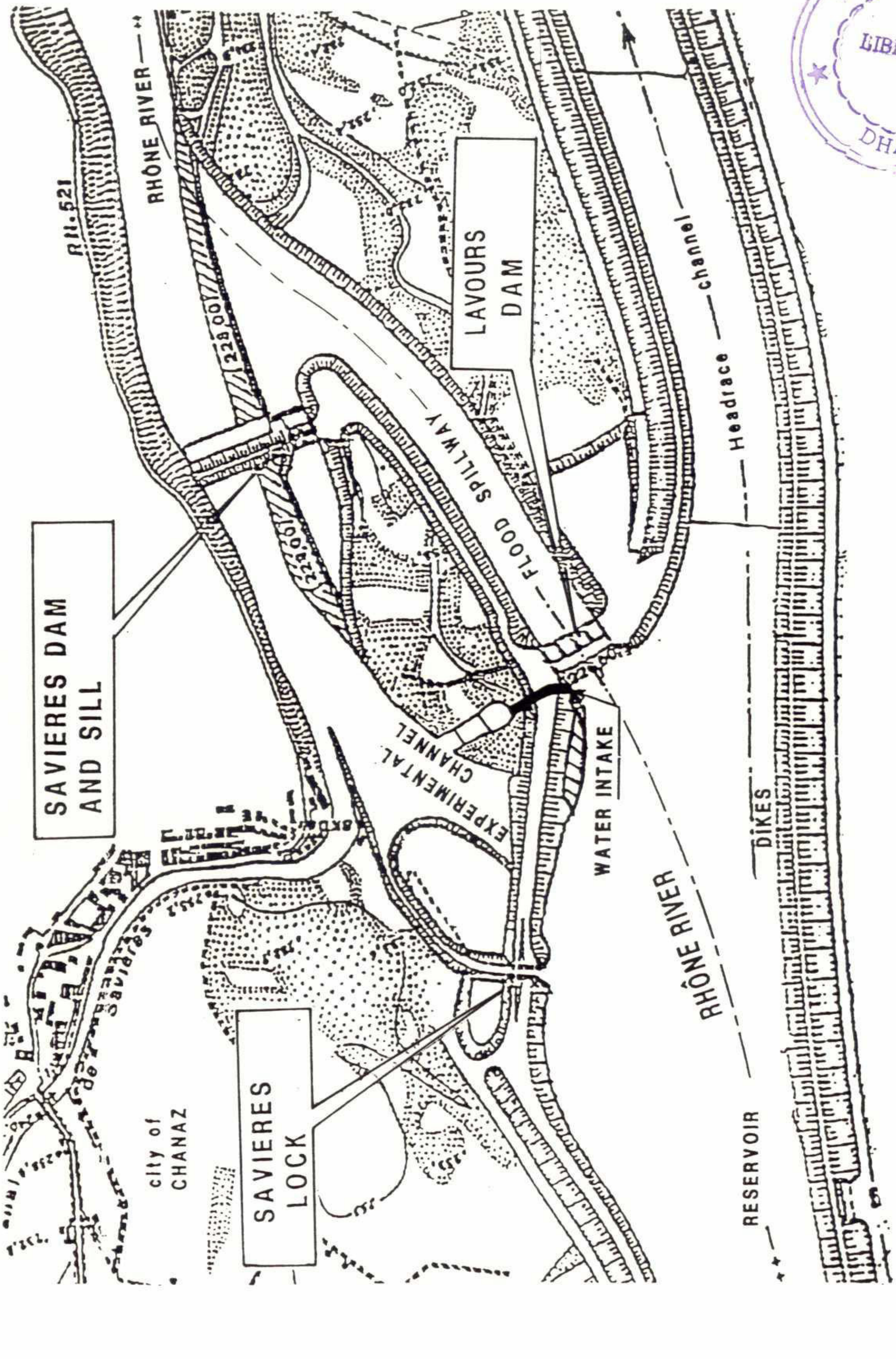
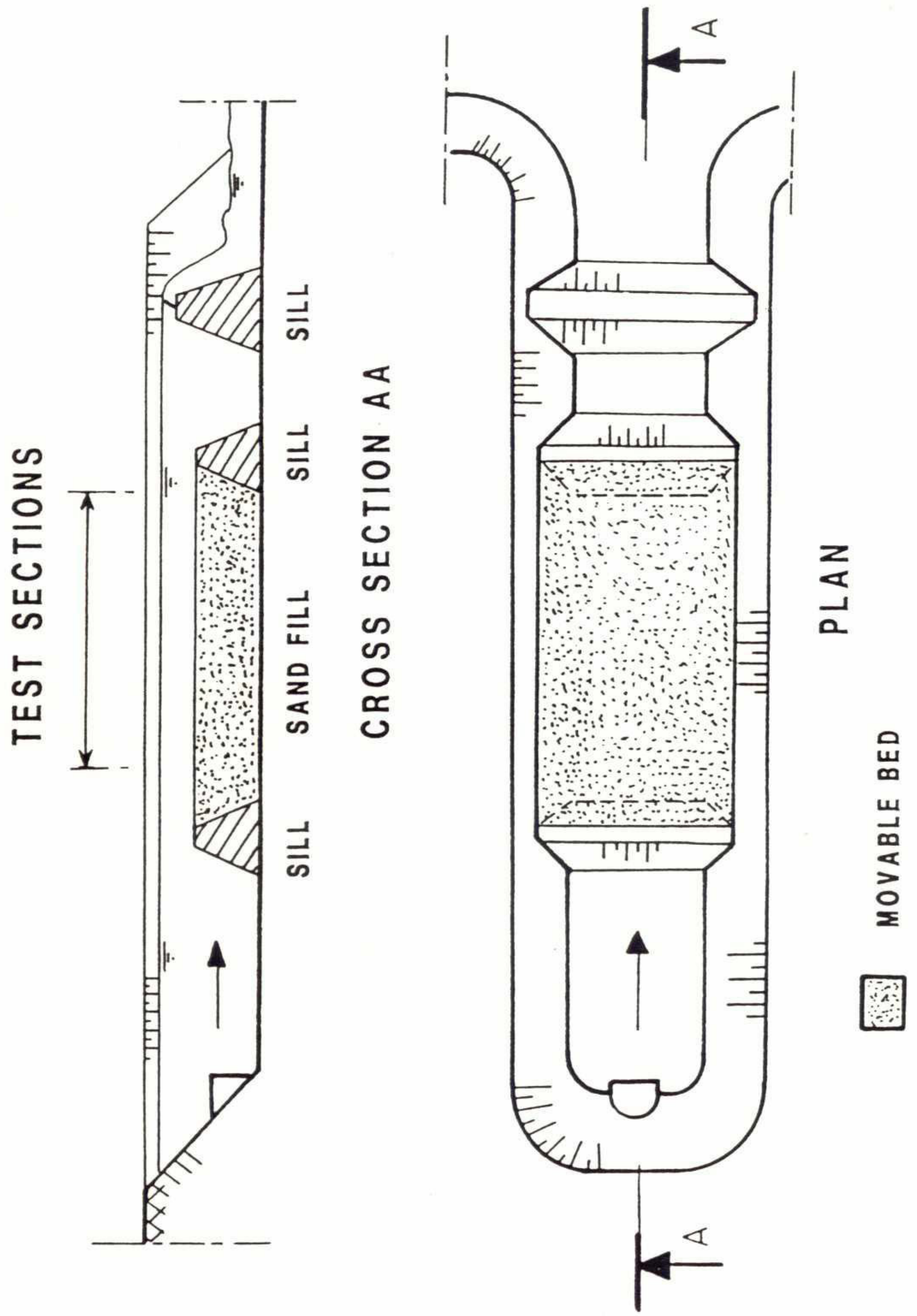


PLAN MODEL SITE	FAP - 21 BANK PROTECTION PILOT PROJECT
	FIG. 3.1



PLAN OF THE FACILITY

FAP - 21

BANK PROTECTION PILOT PROJECT

FIG. 3.2

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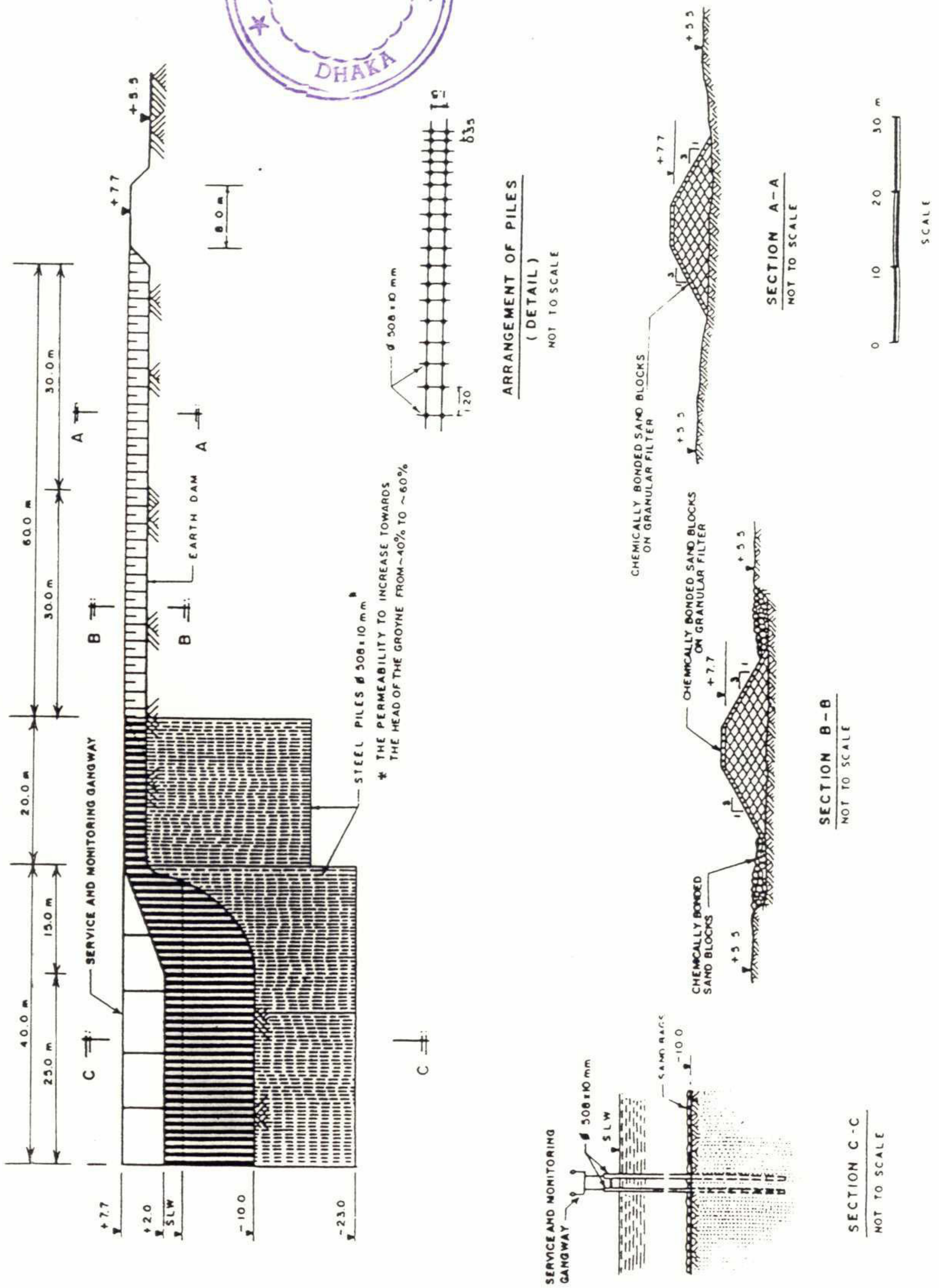
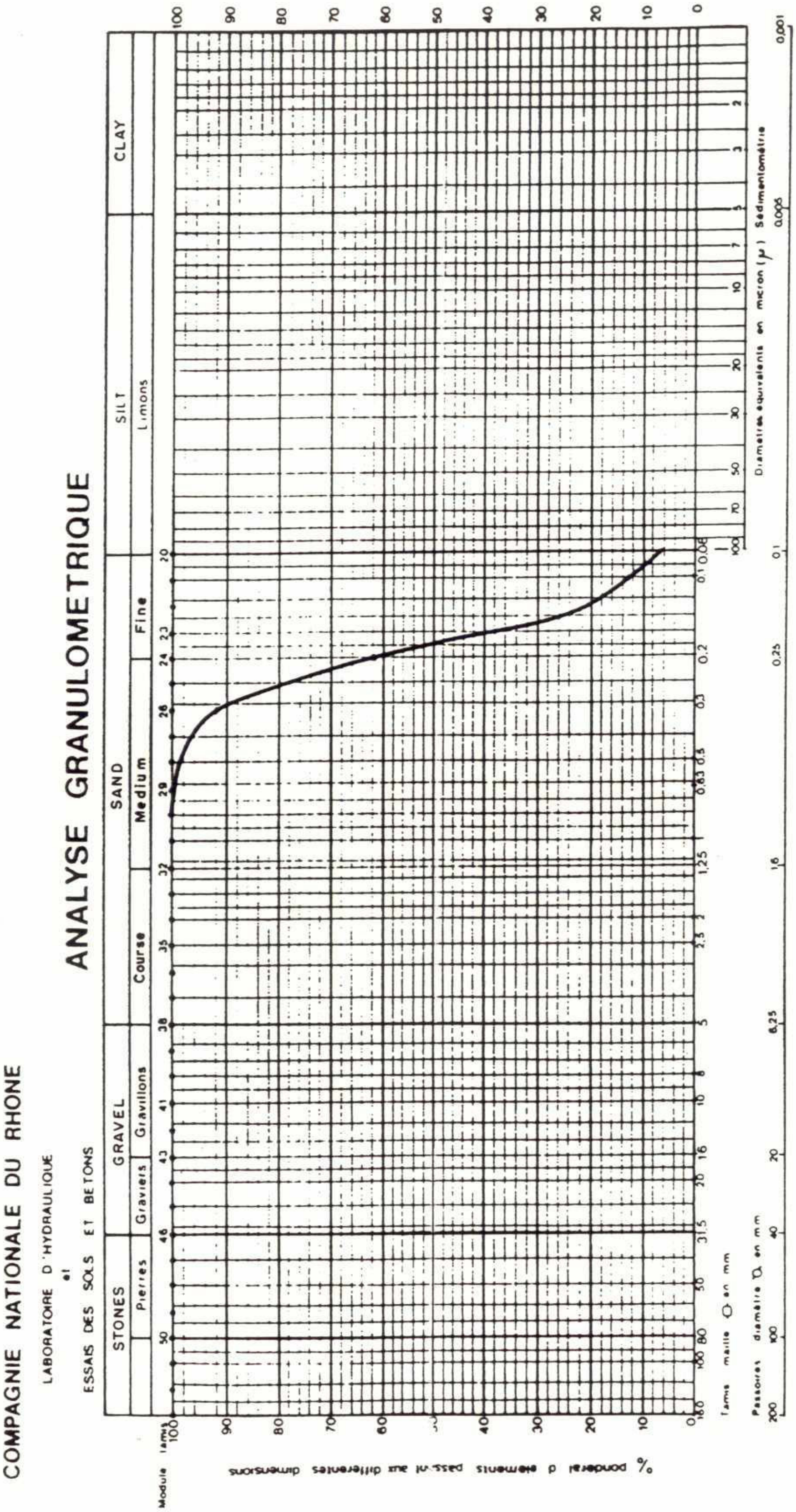
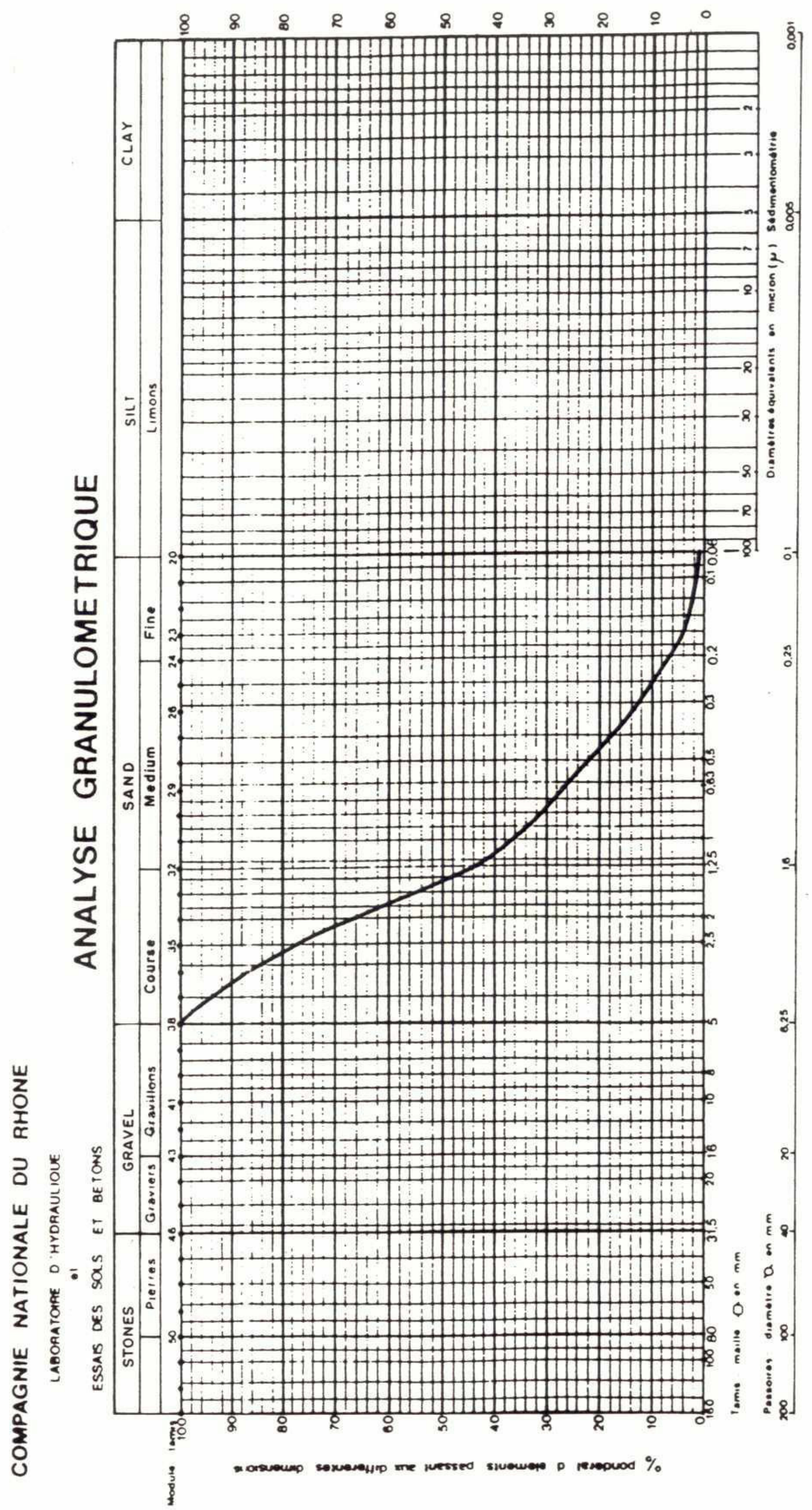


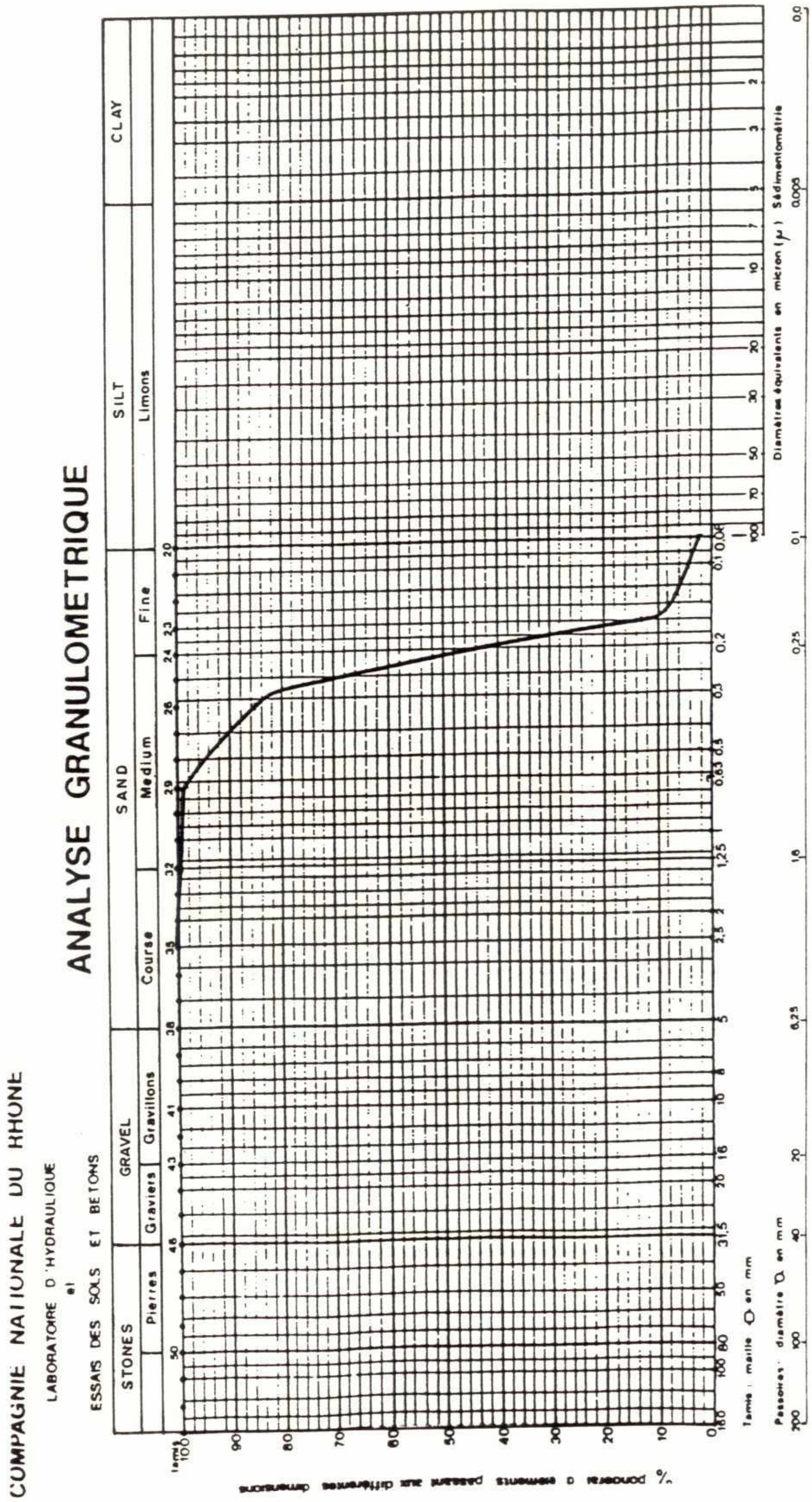
DESIGN OF A PERMEABLE GROYNE	**FAP - 21** **BANK PROTECTION PILOT PROJECT**	
		FIG. 3.3



SIEVING CURVE OF JAMUNA SAND	FAP – 21 BANK PROTECTION PILOT PROJECT FIG. 3.4

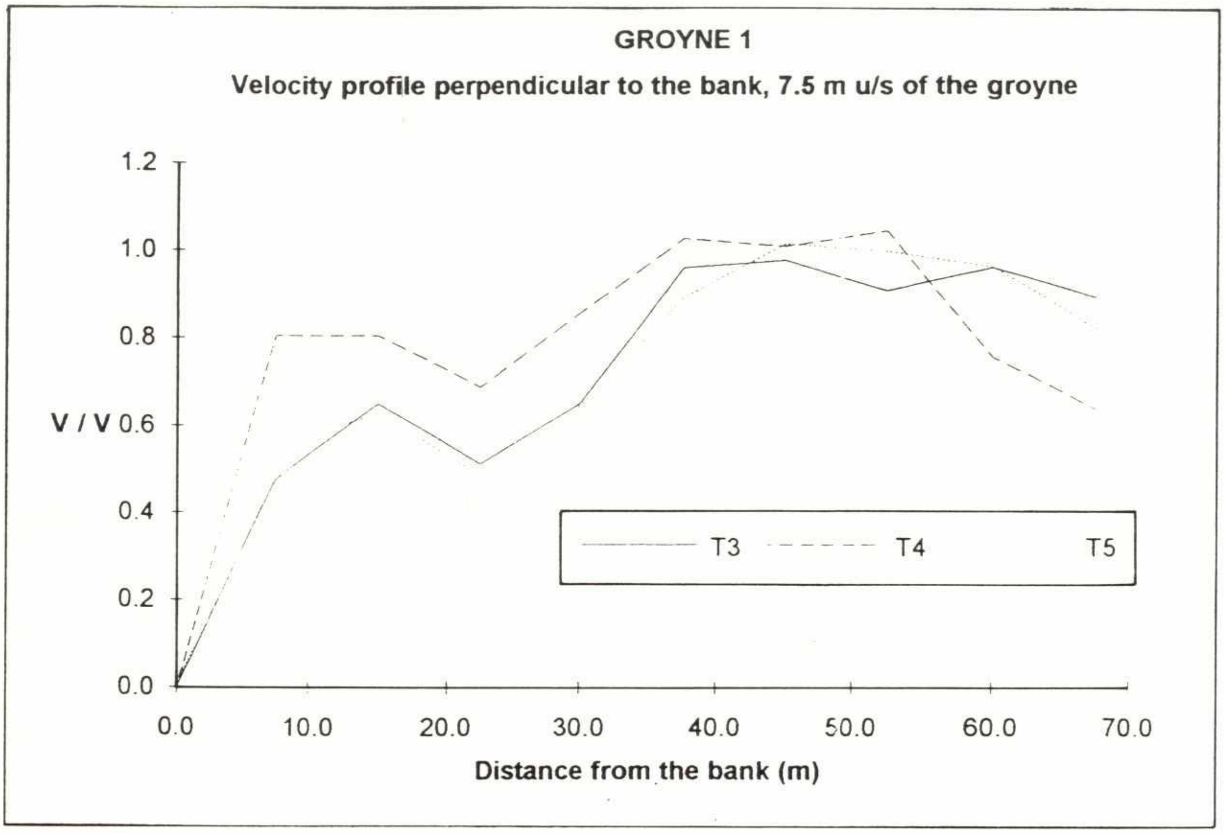


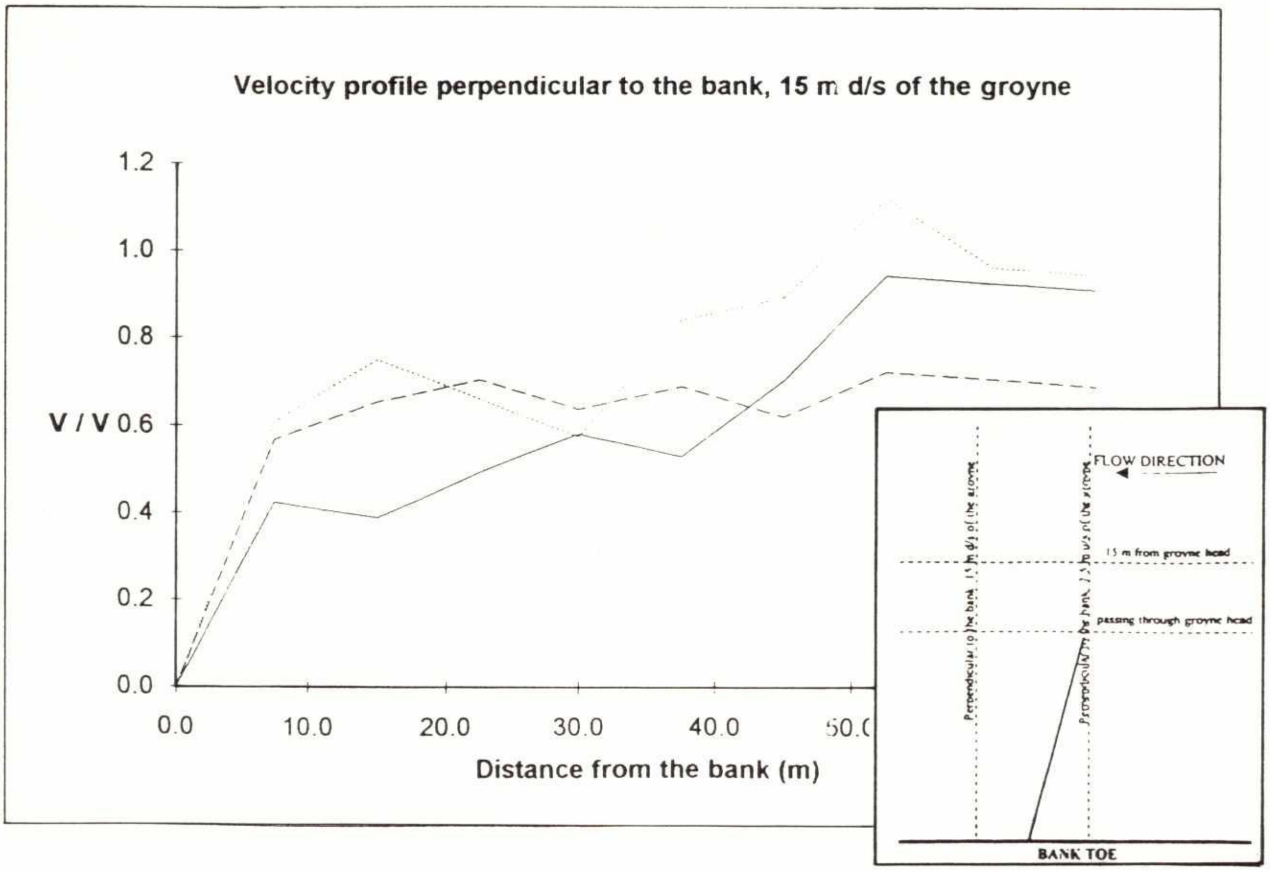
SIEVING CURVE OF MODEL SAND 1	**FAP – 21**
	BANK PROTECTION PILOT PROJECT
	FIG. 3.5



SIEVING CURVE OF MODEL SAND 2	FAP - 21 BANK PROTECTION PILOT PROJECT
	FIG. 3.6

8r



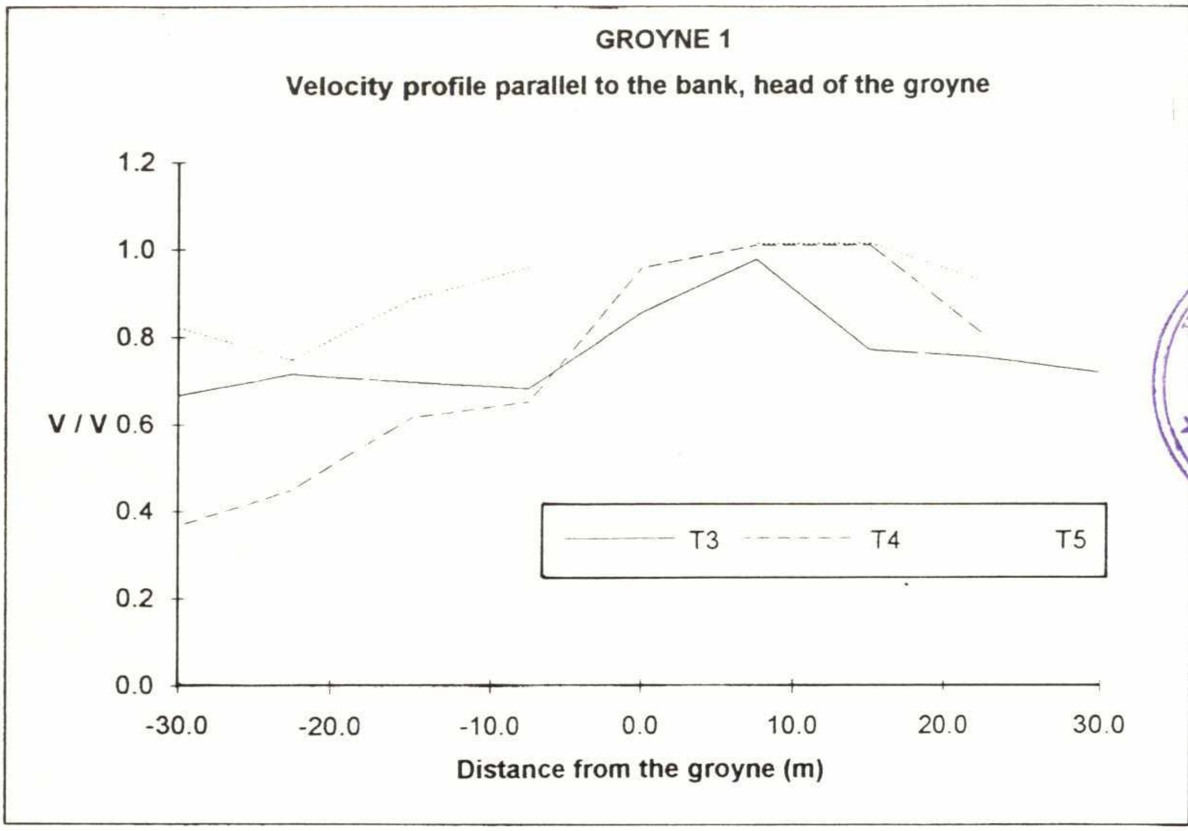


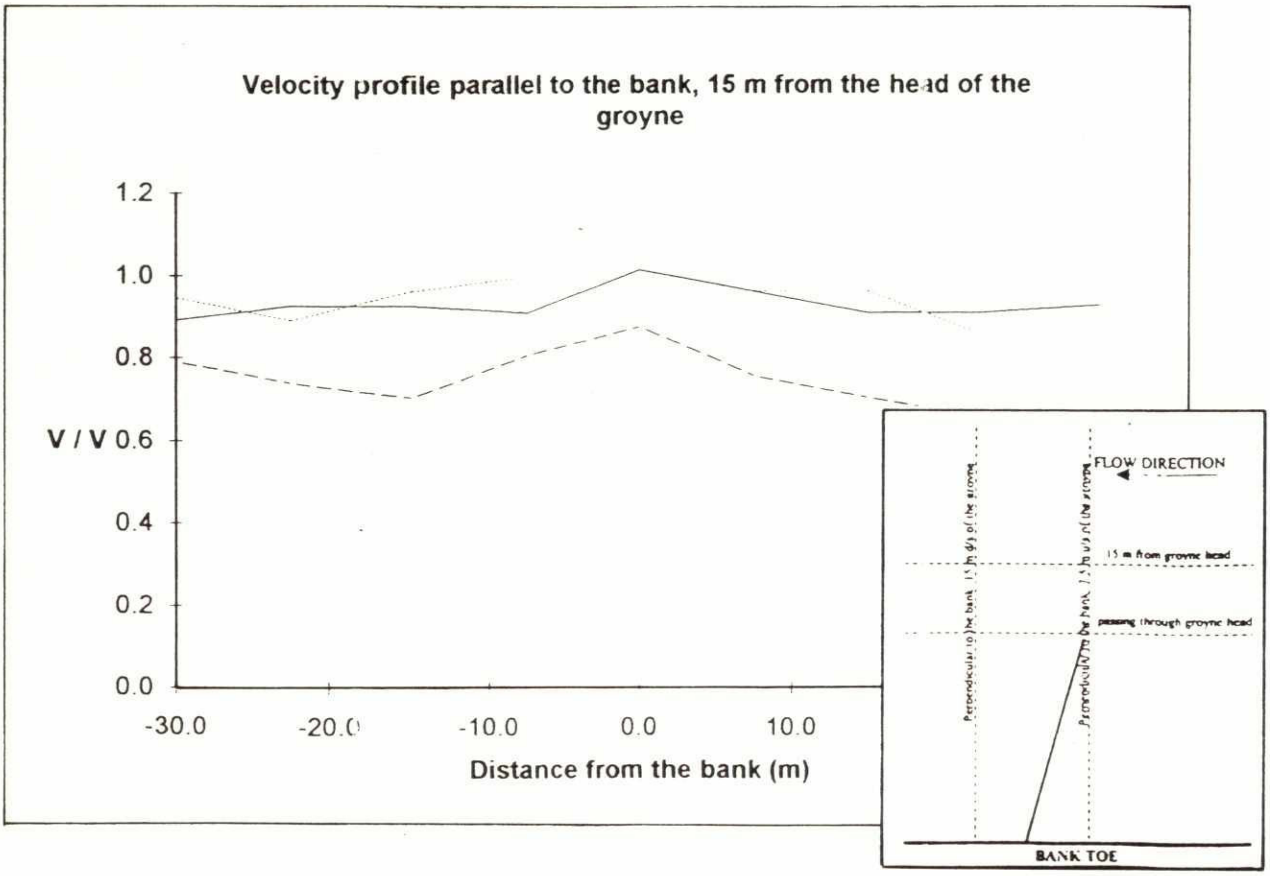
FAP – 21

BANK PROTECTION PILOT PROJECT

VELOCITY PROFILES IN T3,T4 ANDT5

FIG. 6.1-1



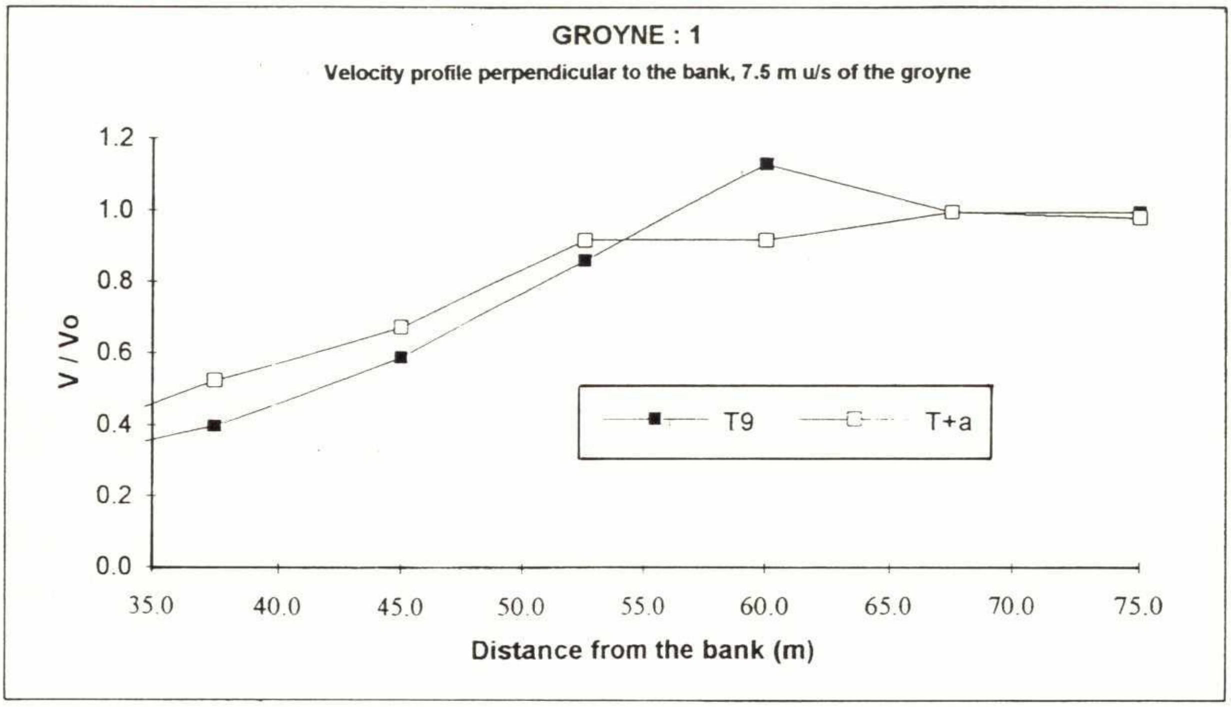


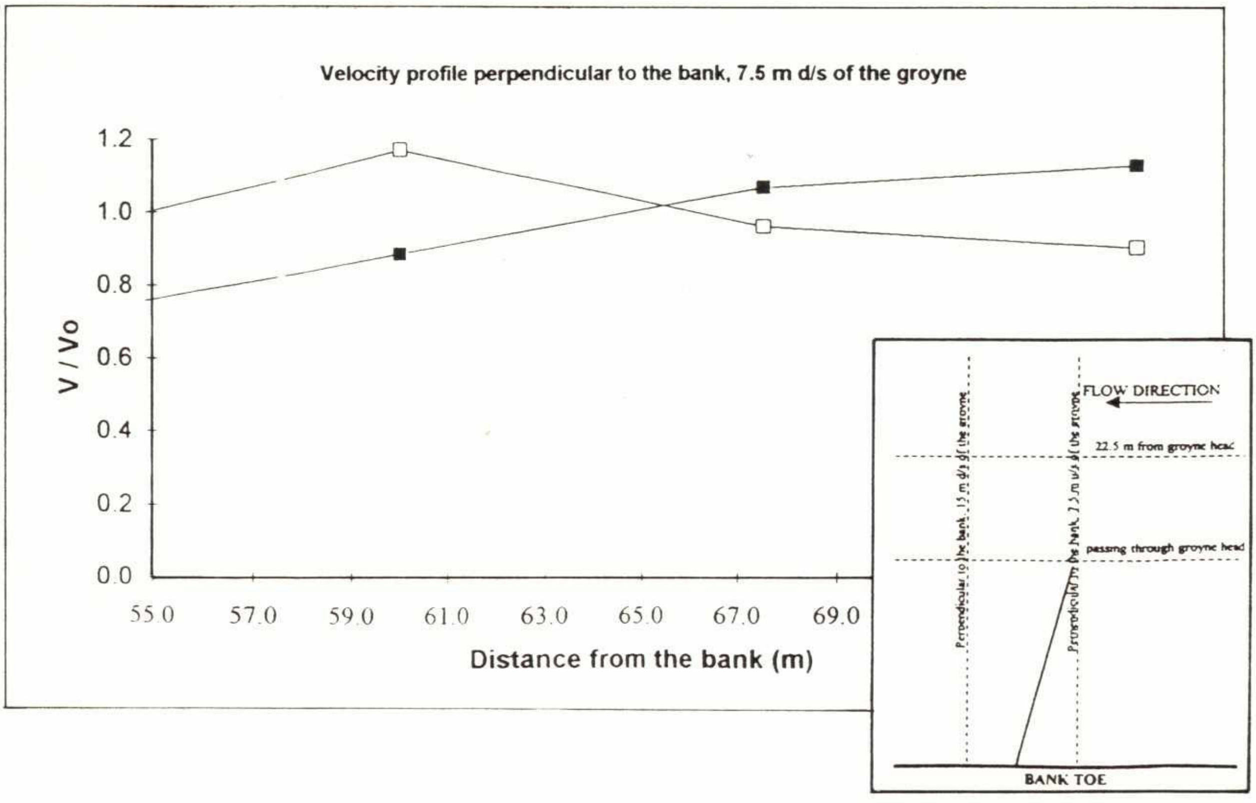
VELOCITY PROFILES IN T3, T4 AND T5

FAP – 21

BANK PROTECTION PILOT PROJECT

FIG. 6.1-2



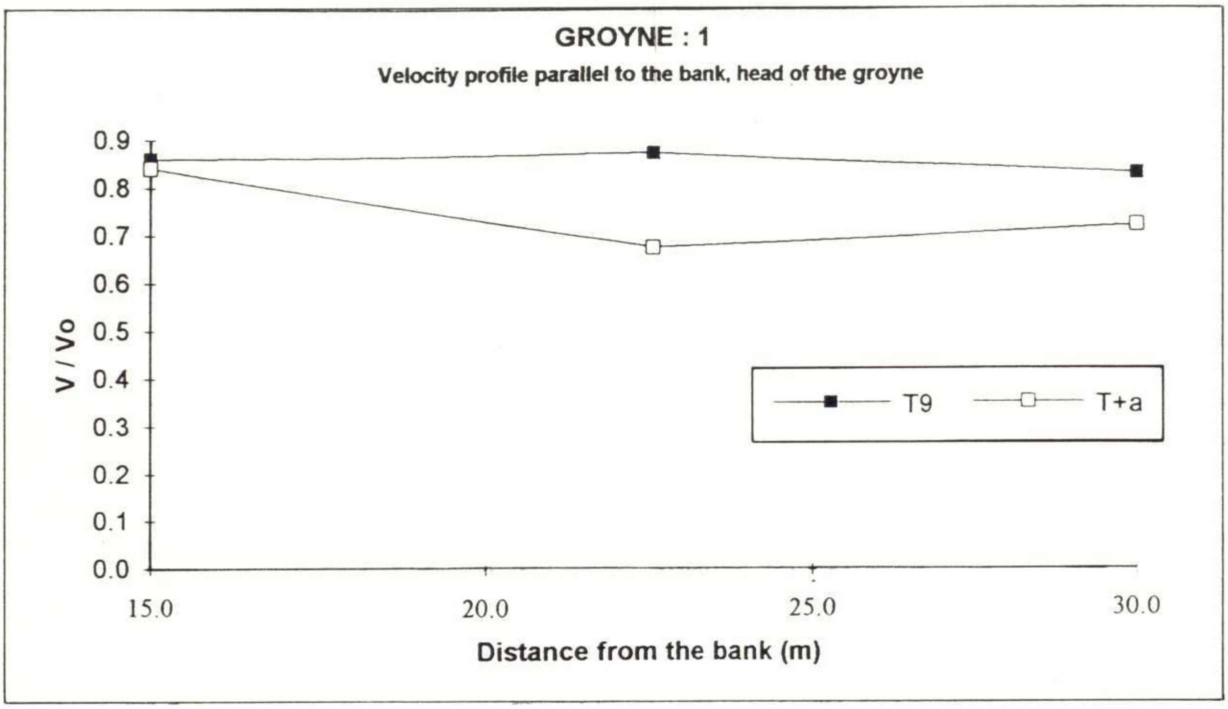


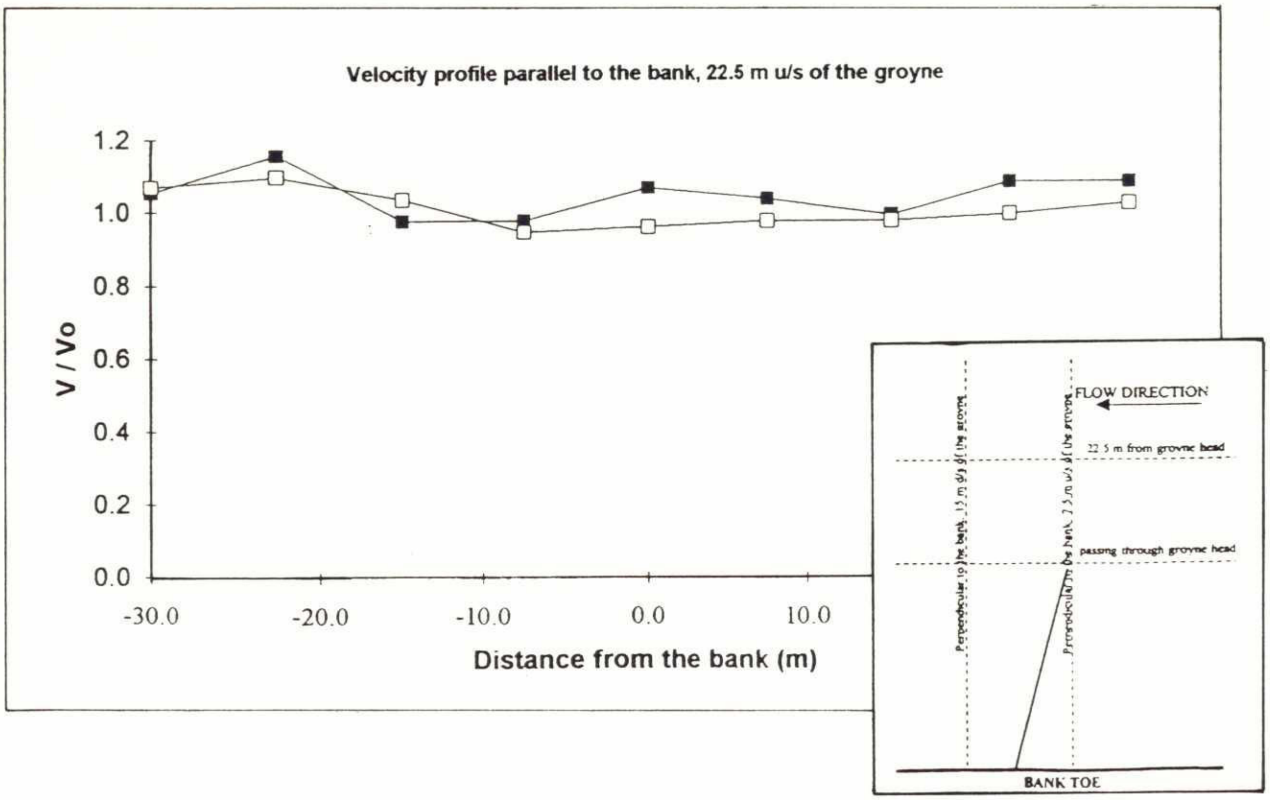
VELOCITY PROFILES IN T9 AND T10 AROUND IMPERMEABLE GROYNE

FAP – 21

BANK PROTECTION PILOT PROJECT

FIG. 6.1-3



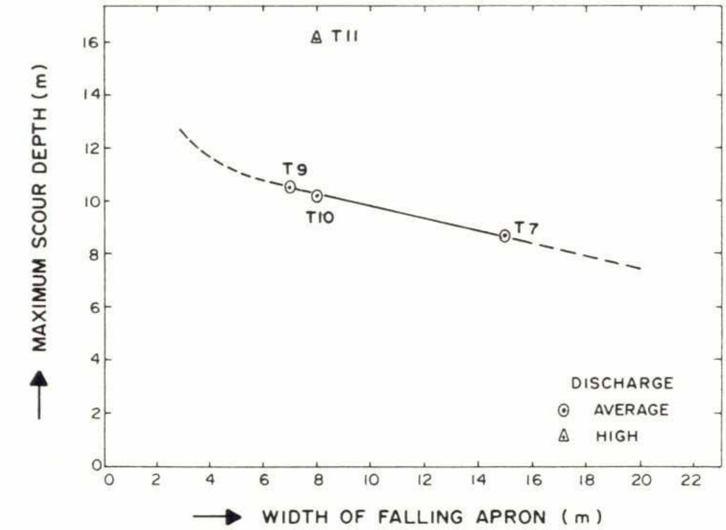


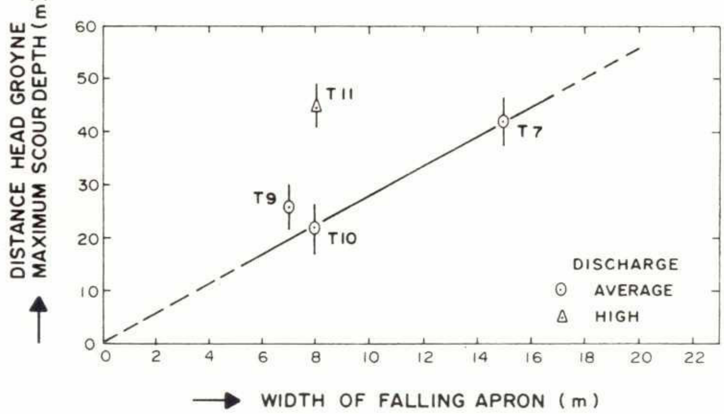
VELOCITY PROFILES IN T9 AND T10 AROUND IMPERMEABLE GROYNE

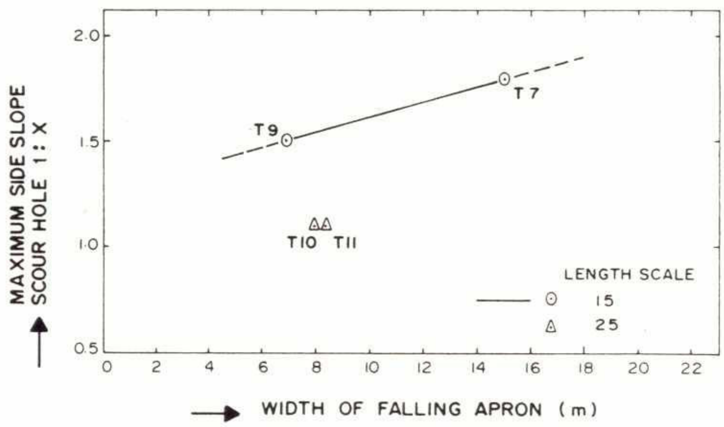
FAP - 21

BANK PROTECTION PILOT PROJECT

FIG. 6.1-4





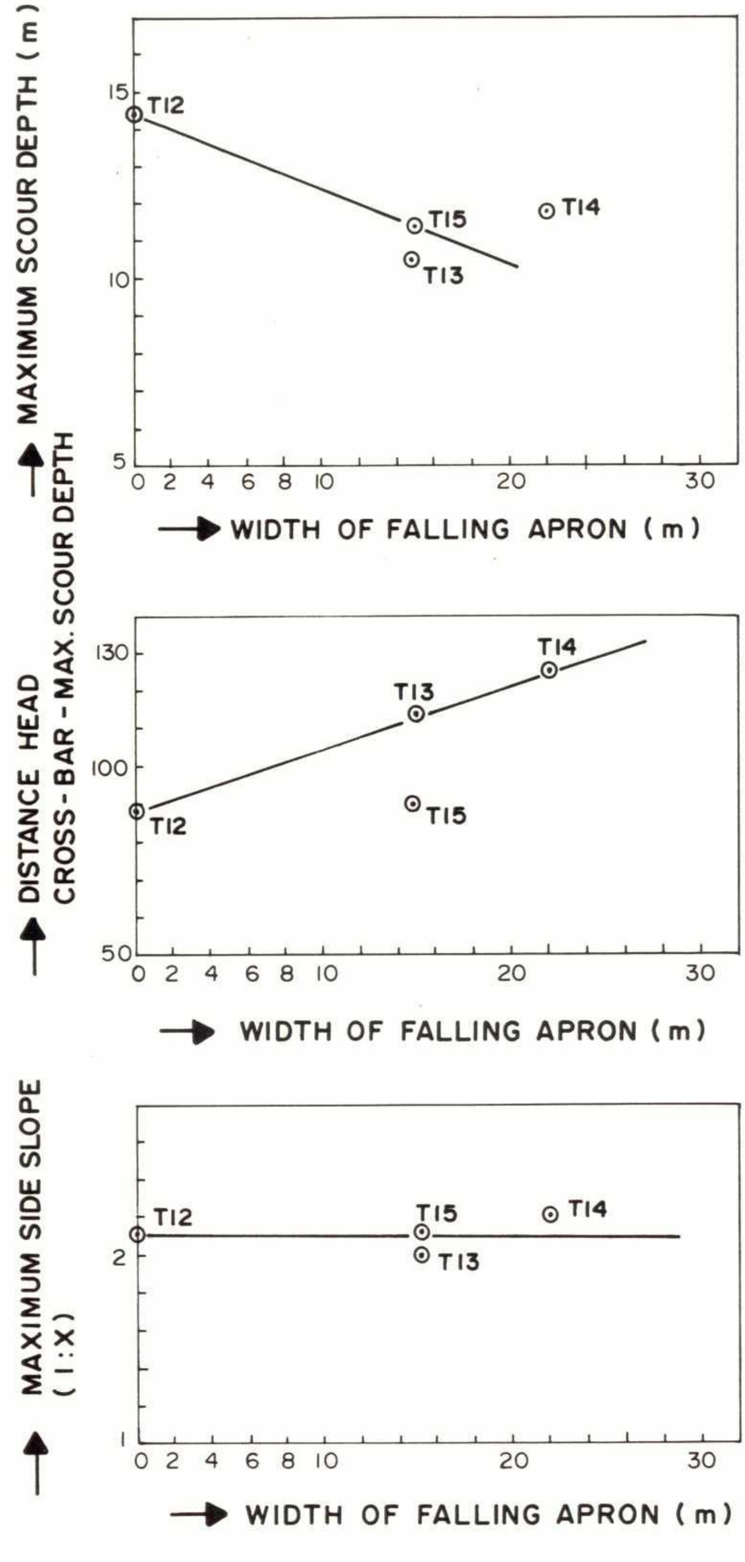


CHARACTERISTICS OF THE SCOUR HOLE AS A FUNCTION OF THE WIDTH OF THE FALLING APRON AROUND AN IMPERMEABLE GROYNE

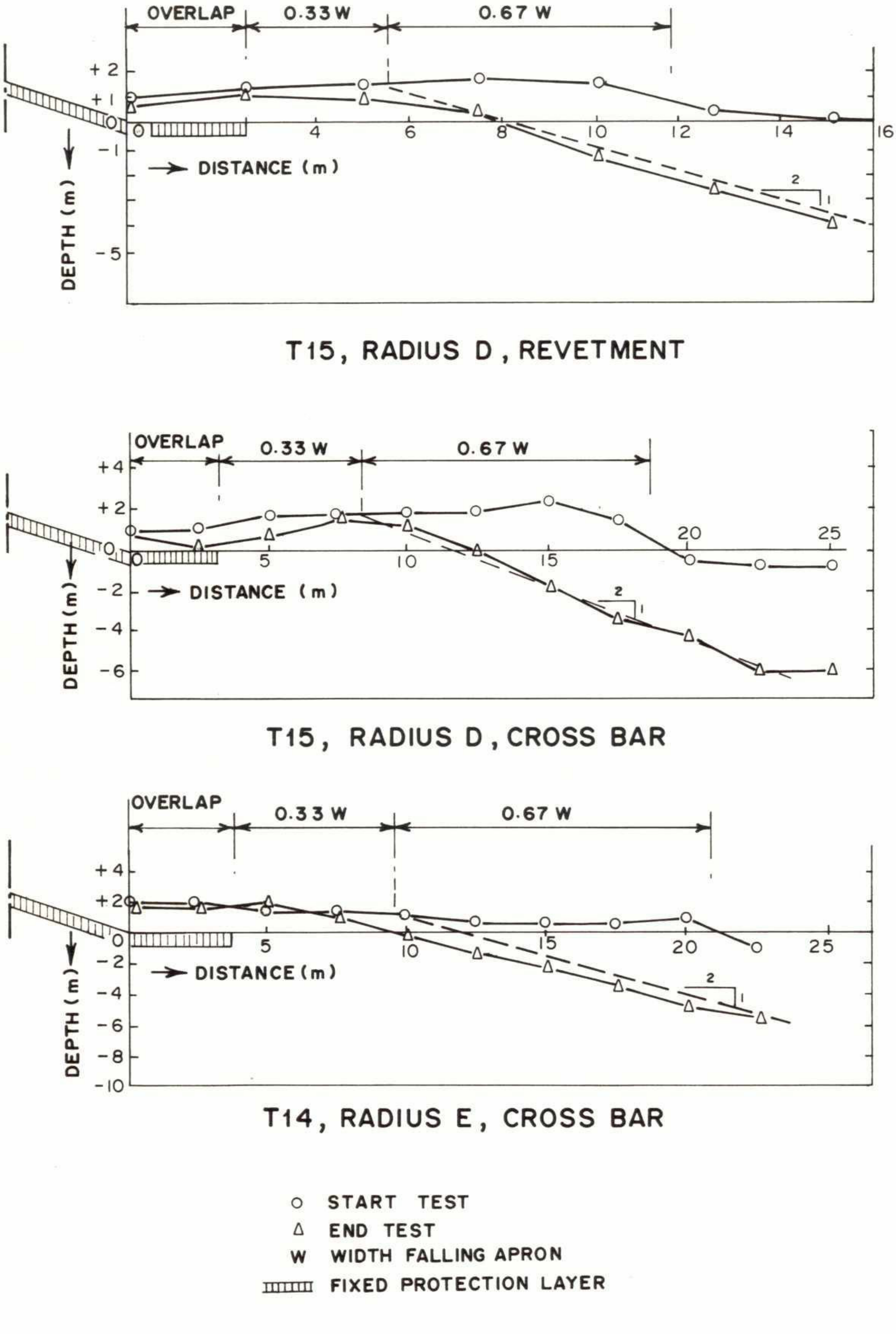
FAP – 21

BANK PROTECTION PILOT PROJECT

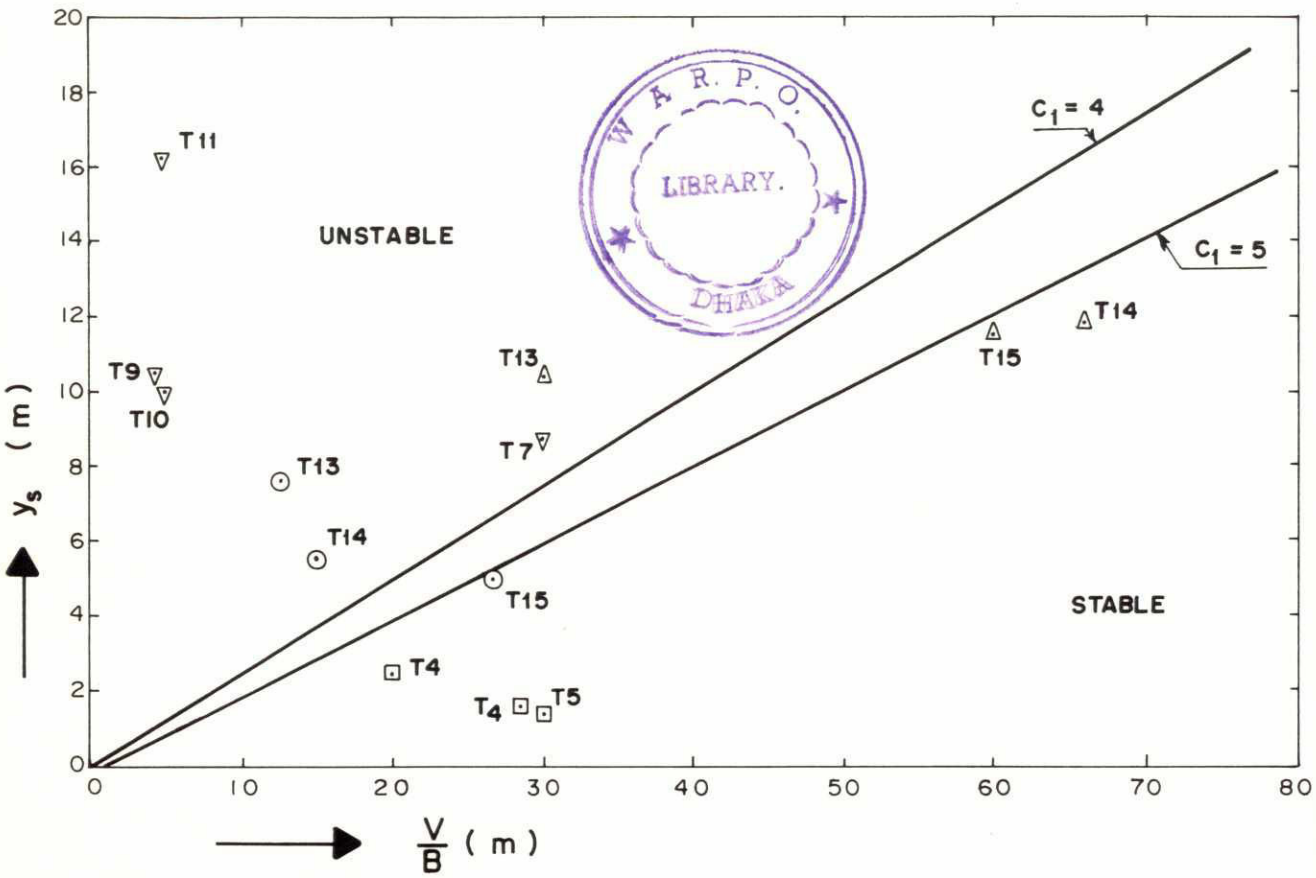
FIG. 6.3 - 1



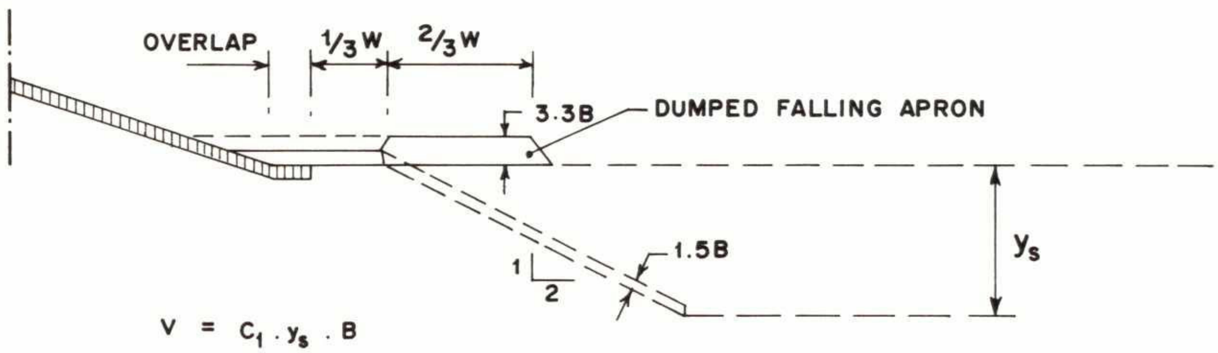
CHARACTERISTICS OF THE SCOUR HOLE AS A FUNCTION OF THE WIDTH OF THE FALLING APRON AROUND A CROSS - BAR	FAP – 21 BANK PROTECTION PILOT PROJECT
	FIG. 6.4 - 1



THE FINAL POSITION OF A FALLING APRON IN T14 AND T15	FAP - 21 BANK PROTECTION PILOT PROJECT
	FIG. 6.4 - 2



REVETMENT
CROSS BAR
IMPERMEABLE GROYNE
PERMEABLE GROYNE



$V = C_1 \cdot y_s \cdot B$

B = BLOCK SIZE (m)

y_s = SCOUR DEPTH (m)

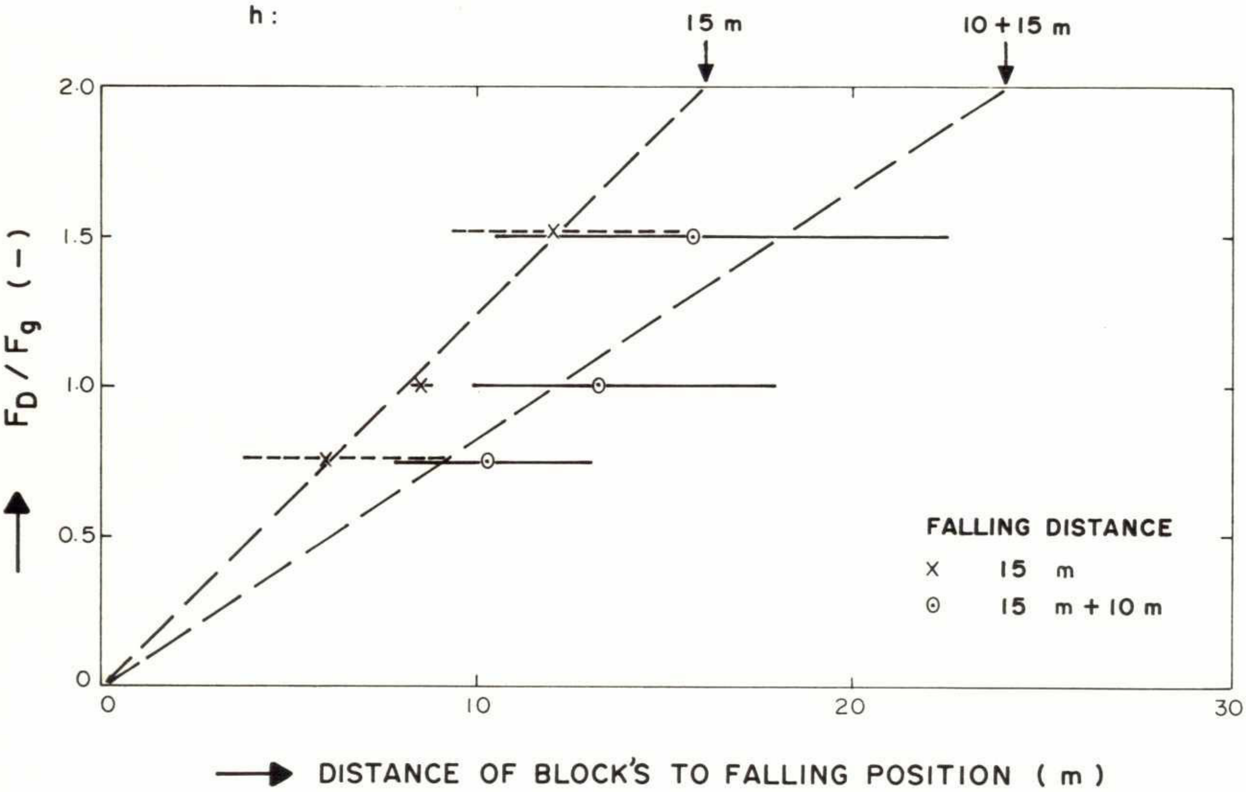
V = VOLUME PER METER (m^2)

DESIGN METHOD OF A FALLING APRON

FAP - 21

BANK PROTECTION PILOT PROJECT

FIG. 6.6-1



DUMPING OF CC-BLOCKS IN FLOWING WATER

FAP-21

BANK PROTECTION PILOT PROJECT

FIG. 6.7-1

APPENDIX 1

PRESENTATION OF THE RESULTS

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TEST 1

OBJECT

Determine the scour around a set of two permeable groynes with a bed protection

DESCRIPTION :

Scale 1/15
Lay out cf T1A
Hydraulics parameters

	H	V	Q
Prototype values	10 m	2.2 m/s	6536 m3/s
Model values	0.67 m	0.57 m/s	7.5 m3/s

Sand

d50	1.4 mm
sieving curve	cf figure 3

Bed protection YES

	U/S groyne	D/S groyne
Lay out	cf T1A	cf T1A
Type	C.C. Blocks	C.C. Blocks
Blocks size (cm)	60 x 60 x 60	120 x 120 x 120
Thickness	2 layers	1 layer
Way of placement	uniform	uniform

Test duration 20 h

RESULTS :

All

Velocity	cf T1C, T1D
Scour	cf T1D
Photographs	cf T1B

Main

	Velocity maximum	Scour detph u/s groyne	Scour detph d/s groyne
Prototype values	2.4 m/s	0.9 m	0.6 m
Model values	0.62 m/s	0.06 m	0.04 m

COMMENTS

The bed protection placed around the piles of the permeable groyne prevents the development of important scour holes

TEST 2

OBJECT

Check the efficiency of permeable groynes (70/70/60/50)
Determine the scour around a set of two permeable groynes without bed protection

DESCRIPTION :

Scale 1/15
Lay out cf T2A
Hydraulics parameters

	H	V	Q
Prototype values	10 m	2.0 m/s	6536 m3/s
Model values	0.67 m	0.52 m/s	7.5 m3/s

Sand

d50	0.2 mm
sieving curve	cf figure 4

Bed protection NO

Test duration 20 h

RESULTS :

All

Velocity	cf T2C and T2D
Scour	cf T2C
Photographs	cf T2B

Main

	Velocity maximum		Scour detph u/s groyne		Scour detph d/s groyne	
Prototype values	2.2	m/s	1.7	m	1.3	m
Model values	0.57	m/s	0.11	m	0.09	m

COMMENTS

The permeable groynes protect the river bank by reducing gradually the flow velocity from the river to the bank
The scour created around the permeable groyne (70/70/60/50) is small

TEST 3

OBJECT

Reproduce the test T1 with a bigger sand as bed material
Observe the scour around two permeable groynes (70/70/60/50) with a bed protection

DESCRIPTION :

Scale 1/15
Lay out cf T3A
Hydraulics parameters

	H	V	Q
Prototype values	10 m	2.0 m/s	6536 m3/s
Model values	0.67 m	0.52 m/s	7.5 m3/s

Sand

d50	0.2 mm
sieving curve	cf figure 4

Bed protection YES

	U/S groyne	D/S groyne
Lay out	cf T1A	cf T1A
Type	C.C. Blocks	C.C. Blocks
Blocks size (cm)	60 x 60 x 60	120 x 120 x 120
Thickness	2 layers	1 layer
Way of placement	uniform	dumped

Test duration 20 h

RESULTS :

All

Velocity	cf T3C, T3D
Scour	cf T3D
Photographs	cf T3B

Main

	Velocity maximum	Scour detph u/s groyne	Scour detph d/s groyne
Prototype values	2.2 m/s	0.8 m	0.9 m
Model values	0.57 m/s	0.05 m	0.06 m

COMMENTS

The scour holes around the two groynes are comparable with the results of T1
The scour is still very small around the structures

TEST 4

OBJECT

Study the scale effect

DESCRIPTION :

Scale 1/25
Lay out cf T4A
Hydraulics parameters

	H	V	Q
Prototype values	10 m	2.5 m/s	12500 m3/s
Model values	0.40 m	0.50 m/s	4 m3/s

Sand

d50	0.2 mm
sieving curve	cf figure 4

Bed protection YES

	U/S groyne	D/S groyne
Lay out	cf T4A	cf T4A
Type	C.C. Blocks	C.C. Blocks
Blocks size (cm)	60 x 60 x 60	60 x 60 x 60
Thickness	2 layers	2 layers
Way of placement	uniform	dumped

Test duration 20 h

RESULTS :

All

Velocity	cf T4C, T4D
Scour	cf T4D
Photographs	cf T4B

Main

	Velocity maximum	Scour detph u/s groyne	Scour detph d/s groyne
Prototype values	2.6 m/s	2.5 m	1.7 m
Model values	0.52 m/s	0.10 m	0.07 m

COMMENTS

The scour hole are a little bit higher than in T3 but there are still small around the structures

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TEST 5

OBJECT

Study the scale effect

DESCRIPTION :

Scale 1/50
Lay out cf T5A
Hydraulics parameters

(the prototype velocity was 3.5 m/s in T5 in order to get a model velocity sufficient to initiate bed motion)

	H	V	Q
Prototype values	10 m	3.4 m/s	33588 m3/s
Model values	0.20 m	0.48 m/s	1.9 m3/s

Sand

d50	0.2 mm
sieving curve	cf figure 4

Bed protection YES

	U/S groyne	D/S groyne
Lay out	cf T5A	cf T5A
Type	C.C. Blocks	C.C. Blocks
Blocks size (cm)	200 x 200 x 200	100 x 100 x 100
Thickness	2 layers	2 layers
Way of placement	dumped	dumped

Test duration 20 h

RESULTS :

All

Velocity	cf T5C, T5D
Scour	cf T5D
Photographs	cf T5B

Main

	Velocity maximum	Scour detph u/s groyne	Scour detph d/s groyne
Prototype values	3.8 m/s	1.4 m	1.4 m
Model values	0.54 m/s	0.03 m	0.03 m

COMMENTS

The scale 1 in 50 is not appropriate to investigate the falling apron behaviour because the scour holes are not deep enough

TEST 6

OBJECT

Estimate the effect of floating debris trapped in the piles of the permeable groyne (70/70/60/50) and reducing the permeability near the groyne head

DESCRIPTION :

Scale 1/15
Lay out cf T6A
Area obstructed 20 m x 2 m
Hydraulics parameters

	H	V	Q
Prototype values	10 m	2.0 m/s	6536 m3/s
Model values	0.67 m	0.52 m/s	7.5 m3/s

Sand

d50	0.2 mm
sieving curve	cf figure 4

Bed protection NO

Test duration 20 h

RESULTS :

All

Velocity	cf T6B, T6C, T6D
Scour	cf T6D
Photographs	cf T6B

Main

	Velocity maximum		Scour detph u/s groyne	
Prototype values	2.2	m/s	2.5	m
Model values	0.57	m/s	0.17	m

COMMENTS

The limited blockage of floating debris simulated in test T6 in front of the groyne head does not lead to important scour hole development.

TEST 7

OBJECT

Observe the falling apron response around impermeable groyne

DESCRIPTION :

Scale 1/15
Lay out cf T7A
Hydraulics parameters

	H	V	Q
Prototype values	10 m	2.2 m/s	6536 m3/s
Model values	0.67 m	0.57 m/s	7.5 m3/s

Sand

d50	0.2 mm
sieving curve	cf figure 4

Bed protection YES

	U/S groyne	D/S groyne
Lay out	cf T7A	
Type	C.C. Blocks	
Blocks size (cm)	60 x 60 x 60	
Thickness	2 layers	
Way of placement	dumped	

Test duration 20 h

RESULTS :

All

Velocity	cf T7C, T7D
Scour	cf T7E, T7F
Photographs	cf T7B, T7D
Falling apron	cf T7F

Main

	Velocity maximum	Scour detph u/s groyne
Prototype values	2.6 m/s	8.7 m
Model values	0.67 m/s	0.58 m

COMMENTS

The fallin apron was not sufficient to avoid the development of a big scour hole downstream of the structure, though the collapsing of blocks in the hole.
The toe of the piles is protected

TEST 8

OBJECT

Estimate the effect of floating debris, like banana trees, trapped by the piles of the permeable groyne

DESCRIPTION :

Scale 1/15
Lay out cf T8A
Area obstructed 60 m x 2 m 40%
Hydraulics parameters

	H	V	Q
Prototype values	10 m	2.0 m/s	6536 m3/s
Model values	0.67 m	0.52 m/s	7.5 m3/s

Sand

d50	0.2 mm
sieving curve	cf figure 4

Bed protection NO

Test duration 20 h

RESULTS :

All

Velocity	cf T8B, T8C
Scour	cf T8D
Photographs	cf T8D

Main

	Velocity maximum		Scour detph u/s groyne	
Prototype values	2.4	m/s	2.7	m
Model values	0.62	m/s	0.18	m

COMMENTS

The risk that floating debris reduce the permeability of the groyne should be taken into account and a falling apron placed around the head of the structure

TEST 9

OBJECT

Observe the falling apron response around impermeable groyne

DESCRIPTION :

Scale 1/15
Lay out cf T9A
Hydraulics parameters

	H	V	Q
Prototype values	10 m	2.2 m/s	6536 m3/s
Model values	0.67 m	0.57 m/s	7.5 m3/s

Sand

d50	0.2 mm
sieving curve	cf figure 4

Bed protection YES

	U/S groyne	D/S groyne
Lay out	cf T9A	
Type	C.C. Blocks	
Blocks size (cm)	60 x 60 x 60	
Thickness	1 layer	
Way of placement	dumped	

Test duration 20 h

RESULTS :

All

Velocity	cf T9D, T9E
Scour	cf T9F, T9G
Photographs	cf T9B, T9C, T9E
Falling apron	cf T9G

Main

	Velocity maximum	Scour detph u/s groyne
Prototype values	2.6 m/s	10.5 m
Model values	0.67 m/s	0.70 m

COMMENTS

A big scour hole forms downstream of the structure. The falling apron is not long enough and the number of blocks sufficient to protect the toe of the impermeable groyne

TEST 10

OBJECT

Estimate the scour depth without bed protection around a permeable groyne
Observe the scour pattern and the falling apron behaviour around an impermeable groyne

DESCRIPTION :

Scale 1/25
Lay out cf T10A
Hydraulics parameters

	H	V	Q
Prototype values	10 m	2.5 m/s	12500 m3/s
Model values	0.40 m	0.50 m/s	4 m3/s

Sand

d50	0.2 mm
sieving curve	cf figure 4

Bed protection YES

	U/S groyne	D/S groyne
Lay out		cf T1A
Type		C.C. Blocks
Blocks size (cm)		60 x 60 x 60
Thickness		1 layer
Way of placement		dumped

Test duration 10 h

RESULTS :

All

Velocity	cf T10C, T10D
Scour	cf T10D, T10E
Photographs	cf T10B
Falling apron	cf T10E

Main

	Velocity maximum	Scour detph u/s groyne	Scour detph d/s groyne
Prototype values	3.3 m/s	3.1 m	10.1 m
Model values	0.66 m/s	0.12 m	0.40 m

COMMENTS

The scour depth is three times less around the unprotected permeable groyne (70/70/60/50) than near the protected impermeable groyne (vertical wall)

TEST 11

OBJECT

Estimate the influence of a higher flow velocity on the scour depth for a permeable groyne (70/70/60/50) and an impermeable one (vertical wall)

DESCRIPTION :

Scale 1/25
Lay out cf T11A
Hydraulics parameters

	H	V	Q
Prototype values	10 m	4.5 m/s	23438 m3/s
Model values	0.40 m	0.90 m/s	7.5 m3/s

Sand

d50	0.2 mm
sieving curve	cf figure 4

Bed protection YES

	U/S groyne	D/S groyne
Lay out		cf T11A
Type		C.C. Blocks
Blocks size (cm)		60 x 60 x 60
Thickness		1 layer
Way of placement		dumped

Test duration 3.5 h

RESULTS :

All

Velocity	cf T11C, T11D
Scour	cf T11D, T11E
Photographs	cf T11B
Falling apron	cf T11E

Main

	Velocity maximum	Scour detph u/s groyne	Scour detph d/s groyne
Prototype values	4.7 m/s	3.7 m	16.2 m
Model values	0.94 m/s	0.15 m	0.65 m

COMMENTS

The scour depth is five times less around the unprotected permeable groyne (70/70/60/50) than near the protected impermeable groyne (vertical wall). The scour does not increase with the velocit while it is the case with the vertical wall

TEST 12

OBJECT

Investigate two types of structure for bank protection: a cross-bar and a revetment
Observe the scour depth of the holes generated by theses structures

DESCRIPTION :

Scale 1/25
Lay out cf T12A
Hydraulics parameters

	H	V	Q
Prototype values	15 m	3.5 m/s	17188 m3/s
Model values	0.60 m	0.70 m/s	5.5 m3/s

Sand

d50	0.2 mm
sieving curve	cf figure 4

Bed protection NO

Test duration 10 h

RESULTS :

All

	Cross-bar	Revetment
Velocity	cf T12D, T12F	cf T12D, T12G
Flow lines	cf T12E	cf T12E
Scour	cf T12F,T12H,T12I	cf T12G, T12H
Photographs	cf T12B, T12C	cf T12B, T12C

Main

	Velocity maximum		Scour detph Cross-bar		Scour detph Revetment	
Prototype values	3.7	m/s	14.4	m	7.4	m
Model values	0.74	m/s	0.58	m	0.30	m

COMMENTS

This test serves as a reference for the following tests
It showed that a structure without bed protection is jeopardized

TEST 13

OBJECT

Investigate two types of structure for bank protection: a cross-bar and a revetment
Define the falling apron to protect the structures

DESCRIPTION :

Scale 1/25
Lay out cf T13A
Hydraulics parameters

	H	V	Q
Prototype values	15 m	3.5 m/s	17188 m3/s
Model values	0.60 m	0.70 m/s	5.5 m3/s

Sand

d50	0.2 mm
sieving curve	cf figure 4

Bed protection YES (see T13C)

	Cross-Bar	Revetment
Lay out	cf T13B	cf T13B
Type	C.C. Blocks	C.C. Blocks
Blocks size (cm)	50 x 50 x 50	25 x 25 x 25
Thickness	2 layers	3.5 layers
Way of placement	dumped	dumped

Test duration 10 h

RESULTS :

All

	Cross-bar	Revetment
Velocity	cf T13D, T13G	cf T13D, T13M
Scour	cf T13G,T13H,T13I	cf T13M, T13N
Photographs	cf T13C,T13E,T13F	cf T13C, T13L
Falling apron	cf T13J, T13K	cf T13O, T13P

Main

	Velocity maximum	Scour detph Cross-bar	Scour detph Revetment
Prototype values	4.0 m/s	10.4 m	7.6 m
Model values	0.80 m/s	0.42 m	0.30 m

COMMENTS

The blocks 25 x 25 x 25 cm are too light to resist to the flow velocity, the blocks 50 x 50 x 50 cm are wo
The falling apron of the revetment failed completely. The falling apron for the cross-bar could be impro

TEST 14

OBJECT

Investigate two types of structure for bank protection: a cross-bar and a revetment
Define the falling apron to protect the structures

DESCRIPTION :

Scale 1/25
Lay out cf T14A
Hydraulics parameters

	H	V	Q
Prototype values	15 m	3.5 m/s	17188 m3/s
Model values	0.60 m	0.70 m/s	5.5 m3/s

Sand

d50	0.2 mm
sieving curve	cf figure 4

Bed protection YES

	Cross-Bar	Revetment
Lay out	cf T14B	cf T14B
Type	C.C. Blocks	C.C. Blocks
Blocks size (cm)	50 x 50 x 50	25 x 25 x 25
Thickness	2 layers	3.5 layers
Way of placement	dumped	dumped

Test duration 10 h

RESULTS :

All

	Cross-bar	Revetment
Velocity	cf T14C, T14F	cf T14C, T14M
Scour	cf T14F,T14G,T14H	cf T14M, T14G
Photographs	cf T14D, T14E	cf T14L
Falling apron	cf T14J, T14K	cf T14N,T14O,T14P

Dumping of additionnal blocks cf T14I

Main

	Velocity maximum	Scour detph Cross-bar	Scour detph Revetment
Prototype values	4.0 m/s	10.4 m	7.6 m
Model values	0.80 m/s	0.42 m	0.30 m

COMMENTS

The blocks 25 x 25 x 25 cm are too light to resist to the flow velocity, the blocks 50 x 50 x 50 cm are w
The falling apron of the revetment failed completely. The falling apron for the cross-bar could be impro

TEST 15

OBJECT

Investigate two types of structure for bank protection: a cross-bar and a revetment
Precise the falling apron lay-out and the number of layers

DESCRIPTION :

Scale 1/25
Lay out cf T15A
Hydraulics parameters

	H	V	Q
Prototype values	15 m	3.5 m/s	17188 m3/s
Model values	0.60 m	0.70 m/s	5.5 m3/s

Sand

d50	0.2 mm
sieving curve	cf figure 4

Bed protection YES

	Cross-Bar	Revetment
Lay out	cf T15B	cf T15B
Type	C.C. Blocks	C.C. Blocks
Blocks size (cm)	50 x 50 x 50	50 x 50 x 50
Thickness	2 to 4 layers	3.5 layers
Way of placement	dumped	dumped

Test duration 10 h

RESULTS :

All

	Cross-bar	Revetment
Velocity	cf T15C, T15E	cf T15C, T15J
Scour	cf T15E, T15F	cf T15J
Photographs	cf T15D	cf T15I
Falling apron	cf T15G, T15H	cf T15K,T15L,T15M

Dumping of additionnal blocks cf T14I

Main

	Velocity maximum	Scour detph Cross-bar	Scour detph Revetment
Prototype values	4.5 m/s	11.4 m	5.0 m
Model values	0.90 m/s	0.46 m	0.20 m

COMMENTS

The cross-bar was better protected than in T14. Just a small portion of the slope is not completely covered by blocks
The falling apron placed along the revetment permitted to protect the toe of the structure but the result was not better than in T14 though the bigger amount of blocks