"the results of these tests provided a good confirmation of the design resistances of the cohesive materials used."

Plunge Pool Scour Studies Using Cohesive Materials in a Hydraulic Model*

by

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Abstract

Rocks in situ do not slump and the traditional technique of using loose gravel in the model consequently cannot give a good representation of scour patterns in the prototype. Thus, a refined modelling technique utilizing cohesive materials (a mixture of granular materials with a paste composed of clay binder, chalk powder, and water) to simulate the plunge pool geology is introduced. This technique is applied to the plunge pool scour investigations in a 1:100 hydraulic scale model of a spillway project for the purpose of defining an adequate flip bucket toe protection system. The methods, procedures, and results of the investigations are presented.

Introduction

Scour below spillways and outlet works cannot be determined theoretically due to the complex boundary conditions associated with such structures. Hence, the use of hydraulic models becomes the only way of understanding the scour mechanism, of developing and testing adequate river bed protective measures, and of estimating the extent of degradation. If scour occurs very near the hydraulic structures to the extent that it affects their stability, then it becomes a serious safety problem. It is not surprising, therefore, that great efforts have been made in establishing similarity criteria and developing hydraulic modelling techniques for scour problems.

Examining plunge pool scour using a hydraulic model is a delicate procedure leaving a large room for engineering judgment. Traditional technique uses loose gravel with grain sizes similar to the average joint spacing of the prototype rocks. With fully developed flow in an undistorted geometrical scale model, the application of the Froude similitude law leads to similarity of the flow velocity distribution and its dynamic effects on the model plunge pool material. Scour depths may not scale to the prototype; but, the model, when operated for a period of time sufficient to produce a stable bed will indicate erosion tendencies in the prototype.

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Rocks in situ do not slump and the use of loose gravel in the model consequently cannot give a good representation of scour patterns in the prototype. Further complications arise when a region of weak rock masses such as a fault zone is present in an environment of relatively strong and stable rocks. It is along these lines that a refined technique of modelling plunge pool scour using cohesive materials (a mixture of granular materials, clay binder, chalk powder, and water) was envisaged. This refined modelling technique was applied to the plunge pool scour investigations on the Magat dam spillway model for the purpose of defining an adequate flip bucket toe protection system. This paper describes the methods, procedures, and results of the investigations.

The Hydraulic Model

Plunge pool scour investigations were performed on a 1:100 scale model of the Magat dam spillway. The model represented a mirror image of the flood spillway, the spillway channel, and a portion of the Magat river bed. Use of the mirror image pattern was dictated by the existence of a basic model basin used previously in studying an abandoned scheme wherein the flood spillway was located on the right bank of the river instead of the left bank. A plan of the model is shown on Figure 1.

The flood spillway headworks, chutes, and flip buckets were made from transparent acrylic plastic sheets enabling exact representation and providing smooth flow surfaces. The shapes of these elements have already been defined from earlier tests made on the model. For areas of natural ground and spillway channel where no scour study was to be made, the model surfaces were constructed of cement mortar. In modelling erodable areas of the plunge pool, the spillway channel bed and banks were made of different combinations of fixed surfaces, loose gravel, and erodable cohesive mixtures.

Discharges were measured by orifice meters and water level measurements were made by staff and point gages. Downstream tailwater level was adjusted by a flap gate.

Prototype Rock Representation on the Hydraulic Model

General Description of Site Geology

The dam site is predominantly underlain by agglomerates. These are fragments of volcanic ejecta called pyroclasts cemented in a matrix. The pyroclasts consist of fine grained to vesicular volcanic rocks while the matrix, for most parts, is composed of fine grained tuffaceous volcanic materials. This rock type is dense and hard when fresh. Unconfined compressive strengths of 200 Kg/cm^2 to 730 Kg/cm^2 were recorded.

Numerous faults and shear zones having a variety of orientations also characterize the dam site (Figure 2). The Magat fault, a wide zone of highly sheared and weathered rocks with a general strike of $S30^oE$ crosses the spillway channel in the plunge pool area. Another lesser but critical fault, the Korokan fault, cuts across the spillway flip bucket and intersects the Magat fault at the left bank of the plunge pool.

The problem of scour risk to the spillway structure particularly the flip bucket, therefore, is related to the presence of zones of weak, weathered, or extremely fractured rock, in critical areas, within a mass of generally sound and possibly very solid rock. This scenario conditioned the pattern of scour tests that were performed in the model.

Characteristics of the Prototype Rocks

Based on discussions with the project geologists, an initial global estimate of the average joint spacing in the rock mass defining the sizes of blocks that could be detached by scour was from 0.3m to 0.5m.

Further information regarding the characteristics of the rocks in the plunge pool area was obtained from additional boreholes. Project geologists' interpretation of this information was presented in a set of drawings prepared by the project designers. The drawings show in plan, the boundaries of rocks, at elevations 60, 80, 100, and 120m, classified according to the following categories:

Rock Category	Description	Average Joint Spacing (m)	Average Unconfined Compressive Strength (Kg/cm^2)
I	highly erodable rocks	0.1	4
II	less erodable rocks	0.4	150
III	relatively durable rocks	1.0	350

Figures 3 and 4 present this preliminary rock quality definition and their relation to the flood spillway flip bucket.

Plunge Pool Geology—Initial Representation

The use of cohesive materials with two different strengths was envisioned to represent the plunge pool rock definition of Figures 3 and 4 in the model. Closer to the spillway flip bucket, category I and II rocks were assumed to be made up of a weak cohesive material and category III rocks by a strong cohesive material. In the plunge pool area further downstream from the bucket, the weak cohesive material resembled the category I rocks while the strong cohesive material simulated the category II and III rocks.

Figure 5 exhibits the initial representation adopted. For simplicity of placing, the contact faces between the cohesive materials were assumed to be vertical. This schematization was meant to provide an indication of the effect of the presence of wide areas of highly erodable rocks within areas of less erodable rocks.

Cohesive Material Development

The cohesive materials used to schematically represent the plunge pool geology were developed in a laboratory test flume 40 cm wide by 67 cm deep. The cohesive materials, a mixture of granular materials and a paste composed of clay, chalk, and water, were tested for initial erosion velocity in a horizontal bed as well as in a sloped side wall. The tests consisted of varying the mix proportions of the paste and measuring the wall flow velocity at which the granular materials started to be plucked out.

Two mixtures with different initial erosion velocities were developed, one using gravel with an initial erosion velocity of 70 cm/s, and the other using plastic granules having an incipient erosion velocity of 45 cm/s. The mixtures developed referred to previously as the "weak" and "strong" cohesive materials are described as follows:

		Weak Cohesive Material	Strong Cohesive Material
Parent Material		Plastic Granules	Gravel
Grain Size Distribution	d_{10}	3	3.1
(in mm)	d_{50}	3.5	3.7
	d_{90}	4.5	6.2
Specific Gravity		1.4	2.7
Mix Proportions by Volume (in percent):			
Parent material		100	100
Clay		4	11
Chalk		15	11
Water		18	20

The shear flow erosion velocities of 45 and 70 cm/s (4.5 and 7 m/s in reality) used in developing the cohesive materials were chosen partly on the basis of the rock qualities described previously and partly on the basis of a visual appraisal of exposed excavation faces at the site. No systematic collection of data or presentation of experience supported this choice other than the following table extracted from SOGREAH Report No. R. 36.1046.3:

Instantaneous Rock Strength (Kg/cm^2)	Average Flow Velocities of Displacement for a Flow Depth of 5 m (m/s)
1000	15.5
500	11
250	7.9
200	6.9
100	5.2

The correlations between rock strengths and flow velocities for the given flow depth are certainly not complete but the figures provided a stated opinion, when combined with other experience, gave an order of magnitude wherein erosion velocities could be assumed.

Scour Tests

Test Procedures

In all the scour tests, the tailwater level followed the rating curve supplied by the project designers. The tailwater was set on the model by means of a by passed flow before opening the spillway to the test discharge.

Flow through the spillway was maintained for a period long enough to obtain a stable scour profile. In comparative tests, a test duration of 3 hours was used. For design verification tests, one hour per discharge was generally adopted. In examining the final design, the test period per discharge was shorter than an hour because of the wide range of flow conditions the model was subjected to.

In documenting the scour tests, the scour patterns before and after the removal of loose materials released from the cohesive binding were made. This enabled maximum scour depths caused by the different discharges to be recorded without stopping the model at each change in flow.

Plunge Pool Excavation Definition and Basic Spillway Flip Bucket Toe Protection System

Earlier tests conducted on the model provided the basis for defining the plunge pool excavations. Due to the heterogeneous nature of the rocks and in order to reduce potential bar formation on the river bed, generous plunge pool excavations were employed. The volume of the plunge pool was made sufficient for good energy dissipation even for flows over 20,000 m^3/s, evenly distributed. The pool was deepened in the upstream direction in relation to the initial design so as to contain nappe impact at all discharges.

Basic flip bucket protection system consisted of a 45^o concrete slab at the toe of the bucket. Figure 5 also shows the plunge pool excavation definition together with the basic bucket toe protection system.

Scour Tests—Series A

Three complete scour tests (Tests A1, A2, and A3) were made with both the weak and strong cohesive materials representing the plunge pool rock definition given previously by Figure 5. For direct comparison with the results of Test A3, a test was made using only the strong cohesive material (Test A4). Complementary tests with loose gravel of different sizes, placed along the bucket toe, were made as checks on the erosion resistances of the cohesive materials (Tests A5 and A6).

Test A1

The effects of uniform spillway flow distribution on the plunge pool was the concern of Test A1. With a minimum reservoir level of el. 193m, discharges of

5,500, 10,900, 15,600, 22,500, and 26,300 m^3/s were successively passed through the spillway, an hour's duration for each discharge.

The resulting scour patterns before and after removal of loose material are shown in Figure 6. Maximum scour depth against the 45° toe protection slab occurred down to el. 80 m.

Test A2

The aim of this test was to examine the outcome of unsymmetrical chute operation on the tow scour. Exploratory tests revealed that closing the left chute produced the most unfavorable result. Testing, therefore, consisted of fully opening all gates other than those controlling the left chute. For a test duration of three hours, a discharge of 17,100 m^3/s was passed through the model with the reservoir fixed at el. 193 m.

As seen in Figure 7, el. 70 m was the deepest scour depth recorded and this took place in the weak material beneath the closed spillway chute.

Test A3

The same flow conditions of Test A2 were applied to this test where some changes in the flip bucket serrations were made. The scour pattern (Figure 8) and scour depths were not significantly different from those of Test A2 for any conclusion to be drawn about the effect of variation in serration dimensions.

Test A4

On the scoured surfaces resulting from Test A3, the initial plunge pool configuration and excavation were rebuilt using only the strong cohesive material. Similar flow conditions of Test A3 were applied.

Figure 9 reveals the resulting scour pattern. Practically no scour occurred on the spillway bucket protection slab toe. The difference in scour depth at the toe as indicated by the outcome of tests A3 and A4 was 30 m as the velocity of resistance to erosion varied from about 4 m/s to 8 m/s. Furthermore, the scour patterns in the impact area and the right bank were very much similar in the two tests, thus, verifying the consistency of the materials used.

Tests A5 and A6

Tests A5 and A6 were designed to check the scouring resistances of the cohesive materials used along the toe of the flip bucket protection slab. This was done by removing the cohesive material along the toe over a depth of 7 m and replacing it by loose gravel of different sizes. Otherwise, the model was left in the state resulting from the previous test. The same flow was applied as in test A4 but for a duration of one hour only.

The results of these tests provided a good confirmation of the design resistances of the cohesive materials used.

Scour Tests — Series B

The characteristics of the rocks that were used in the initial plunge pool representation were based on borehole information. As the site excavation in the spillway channel and plunge pool progressed, inspection of the exposed faces indicated the areas of highly erodable rocks to be more limited in extent than what was assumed initially. The fault zone containing these rocks were found to be narrower and the rocks outside them, although possibly closely jointed, become rapidly firm enough to be considered as approaching the strong cohesive material quality of the model. Consequently, a series of tests (Tests B1, B2, B3, and B4) was made assuming a thinner band of weak cohesive material along the line of the Korokan fault. The definition of the weak and strong cohesive materials for these test series is depicted in Figure 10.

Test B1

Flow conditions were as in Test A3, that is, left chute closed, reservoir at el. 193 m, discharge of 17,100 m^3/s, and 3 hours test duration.

The contoured scour pattern after the removal of loose materials (Figure 11) shows the deepest scour took place in the narrow band of weak material at the toe but it did not go below el. 97 m.

Test B2

To examine an unsymmetrical chute operation more likely to cause deeper scour in the thin band of weak material at the slab toe, flow conditions were changed to the following: orifice spillway shut, full opening of other gates under a reservoir level of el. 193 m, discharge of 19,600 m^3/s, and test duration of 3 hours.

From Figure 12, maximum scour at the slab protection toe went down to el. 75 m and occurred over the full width of the weak material band.

Test B3

This was a stability check test to determine the size of riprap that may be used in replacing the weak rocks near the slab toe. Flow conditions were similar to Test B2 but test duration was limited to one hour.

Riprap sizes with median diameter of about 1.5 were found to be stable as erosion of this material did not happen in the model.

Test B4

As in Test A1, the aim of this test was to determine the effects of uniform flow distribution on toe scour. For an hour each, discharges of 5,500, 10,900, 15,600, and 22,500 m^3/s were routed through the model. In addition, a flow of 31,000 m^3/s was applied for half an hour.

The contoured scour patterns with loose material in place and removed are shown in Figure 13. Scour at the immediate toe of the bucket was confined to the band of weak material, down to el. 93 m as compared to el. 80 m in Test A1 where a wide band of weak material was assumed.

Test on the Final Bucket Toe Protection Design

The results of the previous scour tests (Test series A and B) were considered to provide sufficient coverage of spillway operating conditions and geological situations on which to base the spillway flip bucket toe protection system in relation to the observed rock formation and quality. The basic protection system is made up of a 45° concrete slab at the toe of the bucket. Adaptation of this basic toe protection system to variations in rock qualities can be made by extending the 45° concrete slab further downwards in weak areas. Associated with this extension is the removal of weak rocks and its replacement by large riprap. The final toe protection design and plunge pool excavation definition are portrayed in Figure 14.

Figure 14 also shows, in plan, the locations of the Korokan and Magat faults. It indicates the band of extremely brecciated and sheared material as they appeared on the undisturbed ground surface. The surface band of the Korokan fault is seen to cut across the right corner of the flood spillway.

Longitudinal sections through the spillway and plunge pool are shown on Figures 15 to 18. The Korokan fault plane dips at about 45° in a northwesterly direction. The main band of weak rocks along the fault line falls along the spillway toe protection slab over a considerable part of its width and gets progressively lower towards the left bank. It passes from behind the concrete slab to a position downstream of its toe.

An example of the geologists' definition of the rock character in the different regions can be seen in Figure 16. At the footwall, the rock is "expected to be massive, dense, hard and strong". Over a width of about 10 m along the fault line, the band is indicated as "extensively brecciated and sheared, locally mylonitized, soft and easily erodable". At the hanging wall, the rock is more broken than at the footwall and a sample designation of one area is "highly sheared and brecciated, with thin gouge and clay".

Representation in the model was made by taking a vertical strip with boundaries on the downstream side defined by the intersection of the el. 80 m line with the lower face of the extensively sheared zone and the upstream boundary defined by the intersection of the el. 60 m or el. 65 m line with the upper face of the fault zone. The vertical strip was assumed to be made up of weak cohesive material while areas outside this strip were composed of the strong cohesive material. The resulting model representation together with the spillway flip bucket toe protection arrangement can be seen in Figure 19.

A final test was made to determine the adequacy of the toe protection provided by this design. The design was submitted to a wide range of spillway operating conditions summarized in Table 1.

The contoured scour pattern obtained after removal of loose material is shown in Figure 20. No scour occurred in the riprap protection at the toe of the

45° slab. Similarly, no scour was evident in the platform of cohesive material at el. 90.5 m at the toe of the 45° slab.

Scour of the weak cohesive material on the left bank was accompanied by some bank scour against the 45° toe wall into the strong cohesive material. This formed as a pocket of scour against the wall because of the particular configuration of flow related to the extensive scour on the left bank. Even with uniformly distributed flow, fairly strong return currents were brought back towards the structure because of the large embayment in the bank. This specific area calls for particular attention. Possible strengthening measures such as deepening of the slab

TABLE I
FINAL SCOUR TEST
Spillway Gate Operating Conditions

	Left Chute		Middle Chute			Right Chute		Orifice Chute		Pool Level	Discharge	Tailwater Level	Test Time
Gate No.	1	2	3	4	5	6	7	8	9	m	m^3/s	m	mins. (model)
Gate Opening Arrangement "A" : Ogee gate opening: 3.4 m								Orifice gate opening : 3.0 m.					
1	S*	S	0*	0	0	0	0	0	0	193	4100	108.3	20
2	0	0	0	0	0	S	S	0	0	193	4100	108.3	20
3	0	0	S	S	S	0	0	0	0	193	3400	107.6	20
4	0	0	0	0	0	0	0	S	S	193	4900	108.9	20
5	S	S	0	0	0	S	S	S	S	193	2000	106.2	20
6	0	0	S	S	S	S	S	S	S	193	1400	105.3	20
7	S	S	S	S	S	0	0	S	S	193	1400	105.3	20
"B" : Ogee gate open fully								Orifice gate open fully					
8										193	17100	117.1	20
9										193	17100	117.1	20
10	as for "A" above									193	14300	115.4	20
11										193	19600	118.6	20
12										193	8400	111.6	20
13										193	5600	109.6	20
14										193	5600	109.6	20
"C" : Ogee gates shut								Orifice gate open fully					
15	S	S	S	S	S	S	S	0	0	193	3100	107.5	20
16	S	S	S	S	S	S	S	0	0	182	2590	106.2	20
17	S	S	S	S	S	S	S	0	0	171	1970	105.8	20
18	S	S	S	S	S	S	S	0	0	160	900	104.5	20
"D" : All gates open evenly													
19	0	0	0	0	0	0	0	0	0	193	5500	109.2	30
20	0	0	0	0	0	0	0	0	0	193	10900	112.8	30
21	0	0	0	0	0	0	0	0	0	193	15600	115.7	30
22	0	0	0	0	0	0	0	0	0	193	22500	118.3	5

*S: gate shut; 0: gate open

penetration into the rock bank and rock abutment consolidation need to be applied.

Conclusions

Rocks in situ do not slump and the traditional technique of using loose gravel in the model to simulate the plunge pool geology consequently cannot give a good representation of scour patterns in the prototype. Thus a refined modelling technique utilizing cohesive materials (a mixture of granular materials with a paste composed of clay binder, chalk powder, and water) was introduced. This technique was then applied to the plunge pool scour investigations in a 1:100 hydraulic scale model of a spillway project for the purpose of defining an adequate flip bucket toe protection system.

Agglomerates are the predominant rock type in the area. This rock type is dense and hard when fresh. However, numerous faults and shear zones containing highly sheared and weathered rocks are also characteristic of the area. The problem of scour risk to the spillway flip bucket structure, therefore, is related to the presence of zones of weak, weathered, or extremely fractured rocks, in critical areas, within an environment of generally sound and possibly very solid rocks. This scenario conditioned the pattern of scour tests in the model.

Project geologists' interpretation of the rock characteristics in the plunge pool area formed the basis of representation in the model. Two cohesive materials of different strengths were envisioned to represent the plunge pool geology. This schematization was meant to provide an indication of the effect of the presences of areas of highly erodable rocks within areas of less erodable rocks.

The two cohesive materials, developed in a laboratory test flume, utilized gravel (referred to as the strong cohesive material) having an initial erosion velocity of 70 cm/s (7 m/s in reality), and the other (referred to as the weak cohesive material) used plastic granules with an initial erosion velocity of 45 cm/s (4.5 m/s in reality).

With both weak and strong cohesive materials resembling the prototype rocks in the plunge pool, scour tests were performed on the model. Sufficient coverage of spillway operating conditions and geological situations on which to base the spillway flip bucket toe protection system in relation to the observed rock formation and quality were made.

The basic spillway flip bucket toe protection system consisted of a 45° concrete slab at the toe of the bucket. Adaptation of this basic toe protection system to variations in rock qualities was made by extending the 45° concrete protection slab further downwards in weak areas. Associated with this extension was the removal of weak rocks and its replacement by large riprap.

The final flip bucket toe protection design was subjected to a wide spectrum of spillway operating conditions. Satisfactory performance of the toe protection system was observed. However, some scour against the 45° toe wall was noticed on the left abutment. Strengthening measures such as deepening of the slab penetration into the rock bank and rock abutment consolidation needs to be applied.

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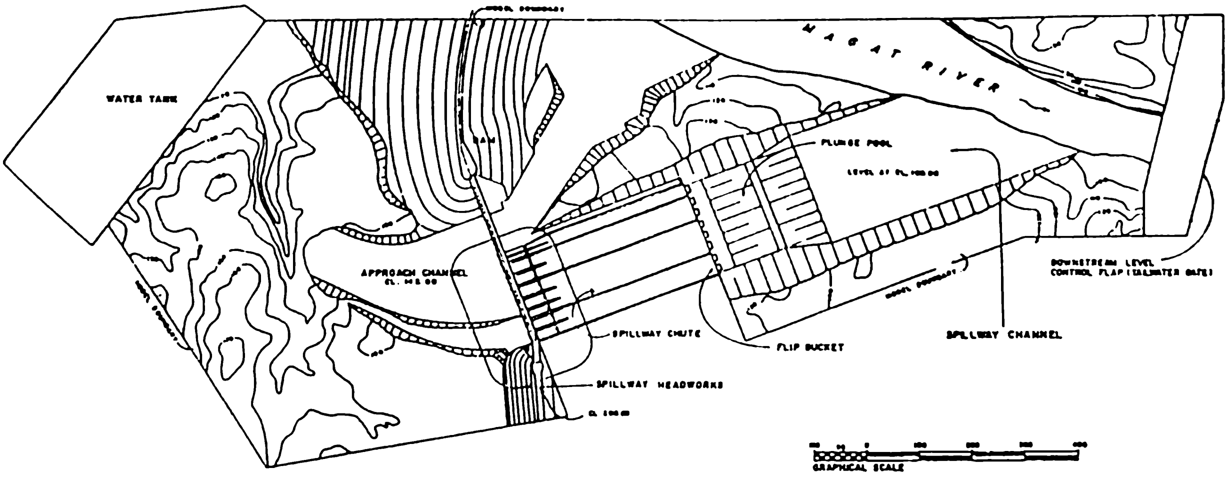


Figure 1. Plan of the 1:100 Mirror Image Model of the Magat Dam Spillway

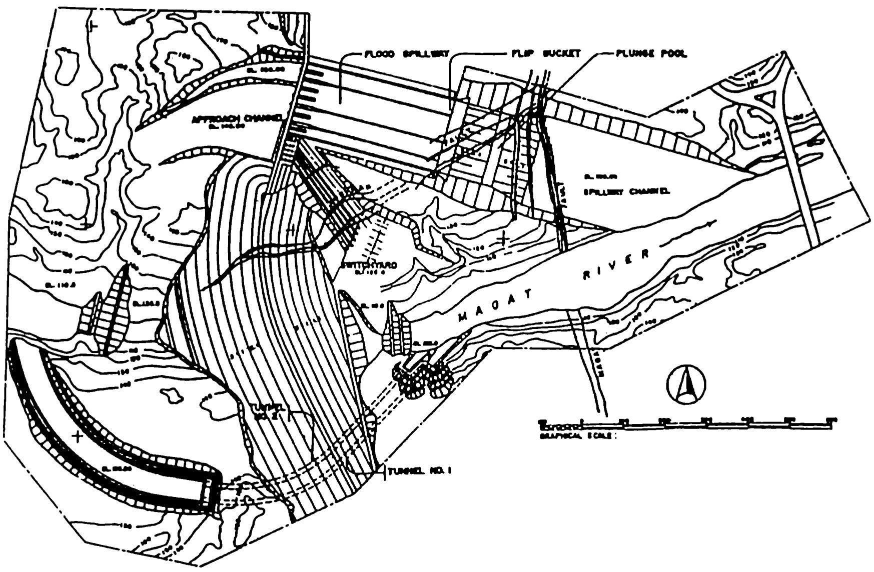


Figure 2. General layout of the dam site showing fault lines

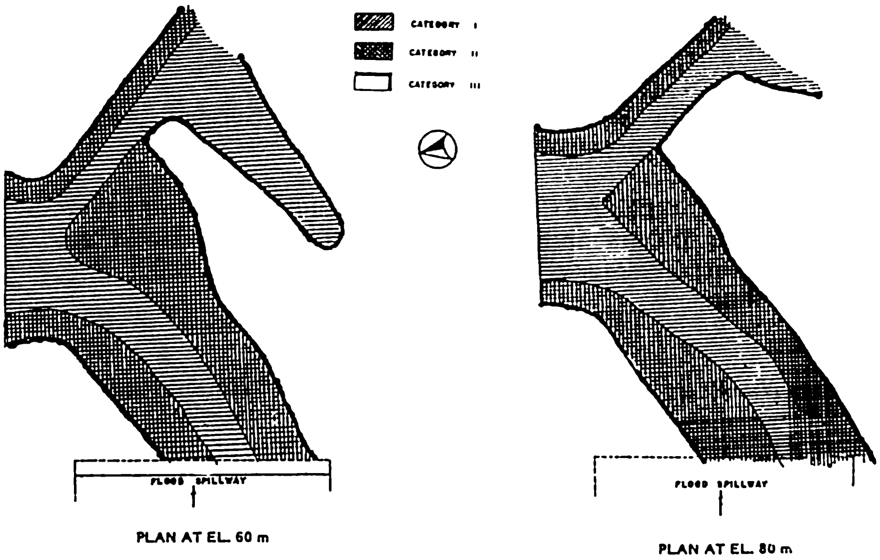


Figure 3. Preliminary plunge pool rock quality definition at el. 60 m and el. 80 m

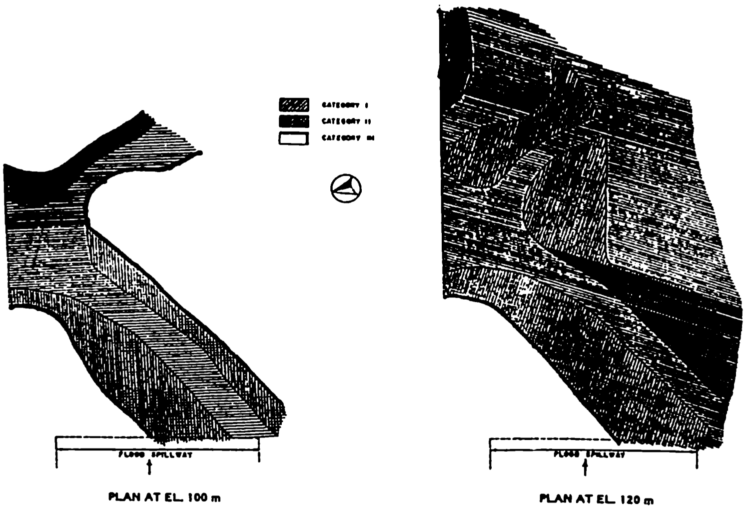


Figure 4. Preliminary plunge pool rock quality definition at el. 100 m and el. 120 m

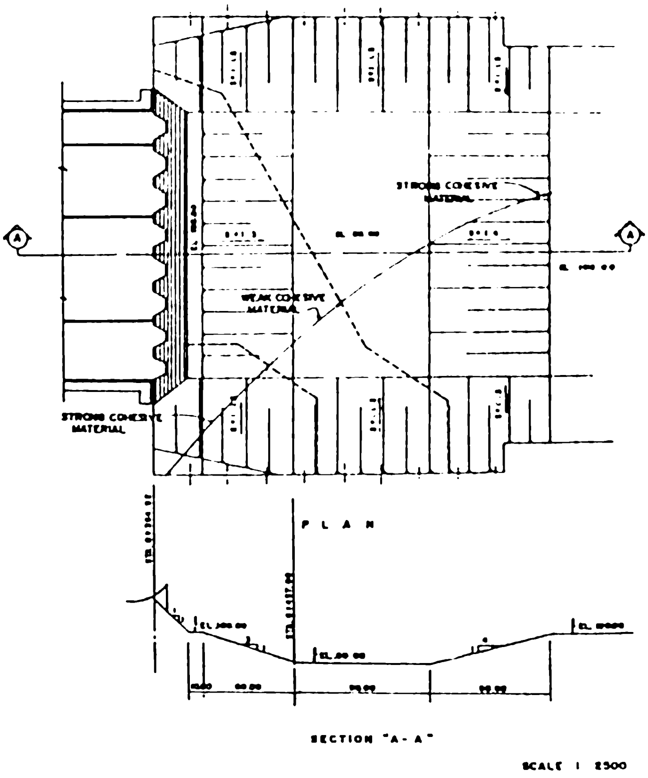
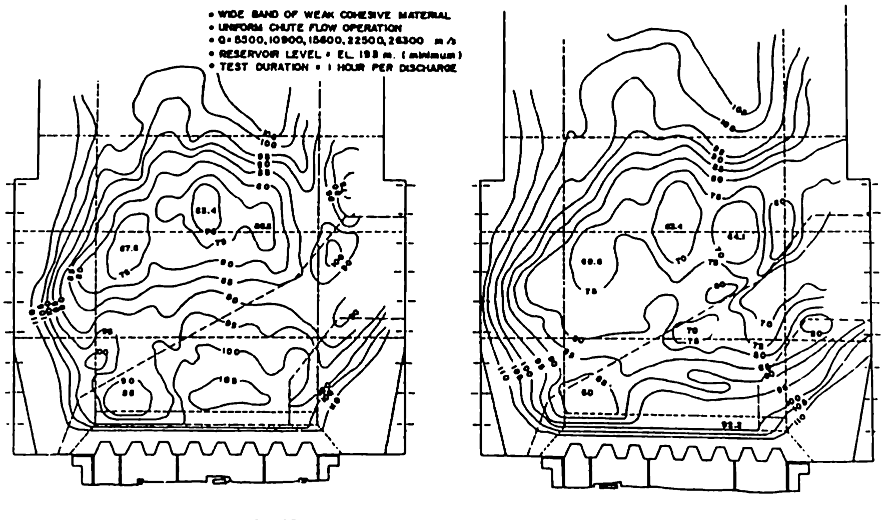


Figure 5. Model representation of plunge pool – test series A



LOOSE MATERIAL IN PLACE

LOOSE MATERIAL REMOVED

Figure 6. Scour patterns – Test A1

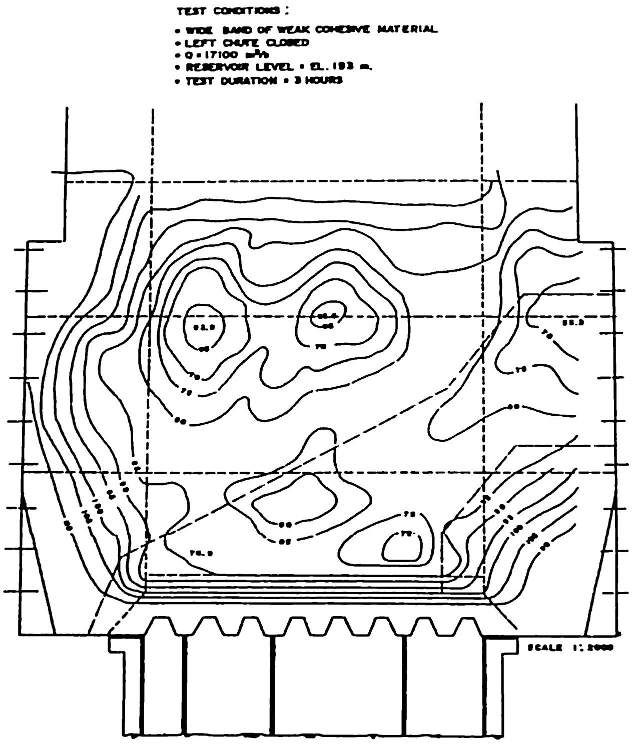


Figure 7. Scour Pattern – Test A2

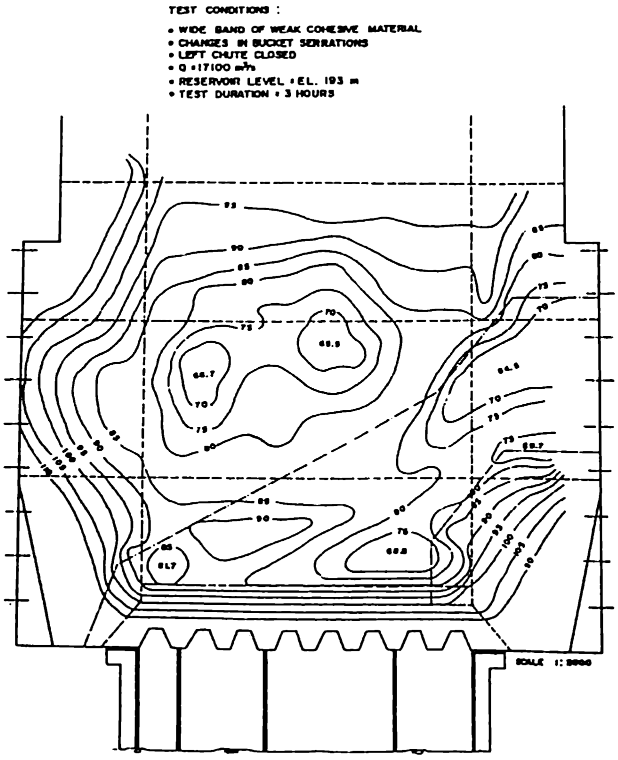


Figure 8. Scour Pattern – Test A3

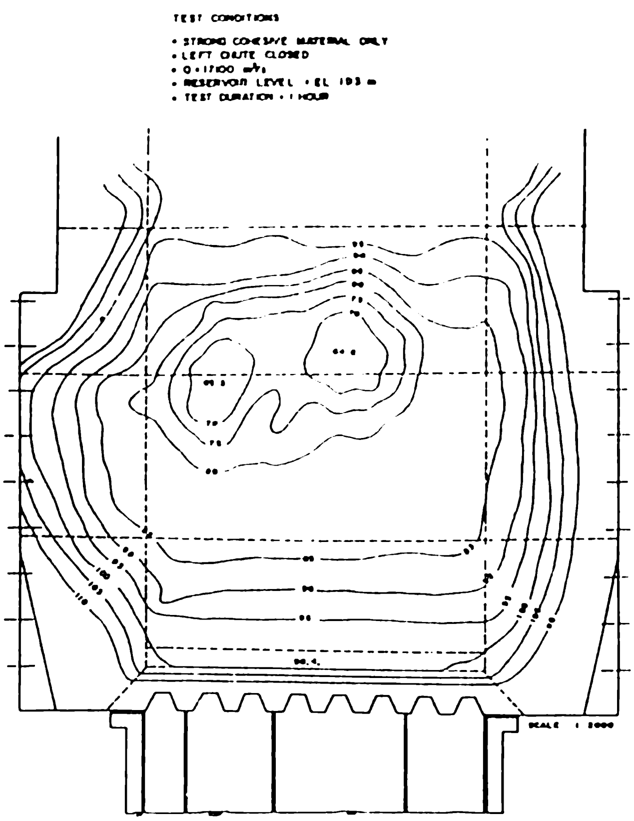


Figure 9. Scour Pattern – Test A4

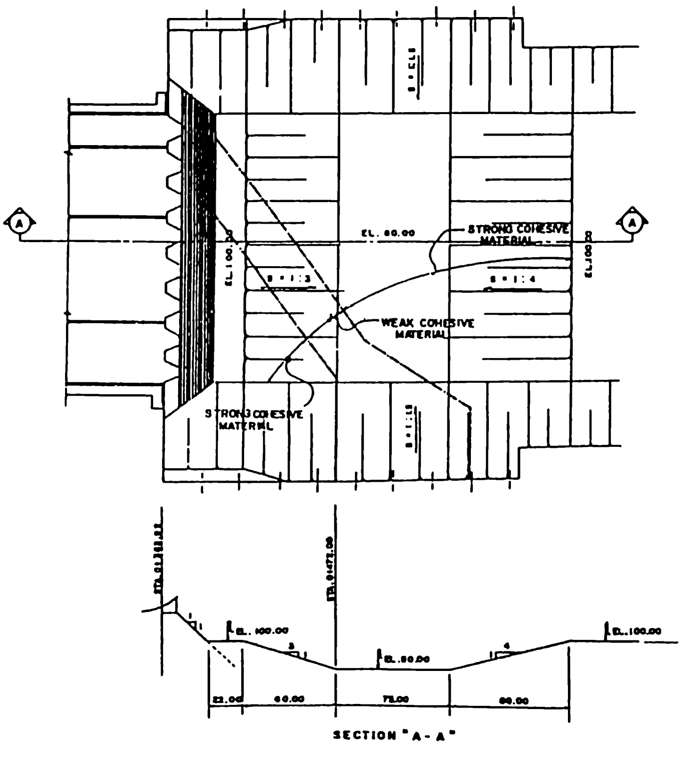


Figure 10. Model representation of plunge pool – test series B

TEST CONDITIONS :

- NARROW BAND OF WEAK COHESIVE MATERIAL
- LEFT CHUTE CLOSED
- Q = 17100 m^3/s
- RESERVOIR LEVEL = EL. 193 m.
- TEST DURATION = 3 HOURS

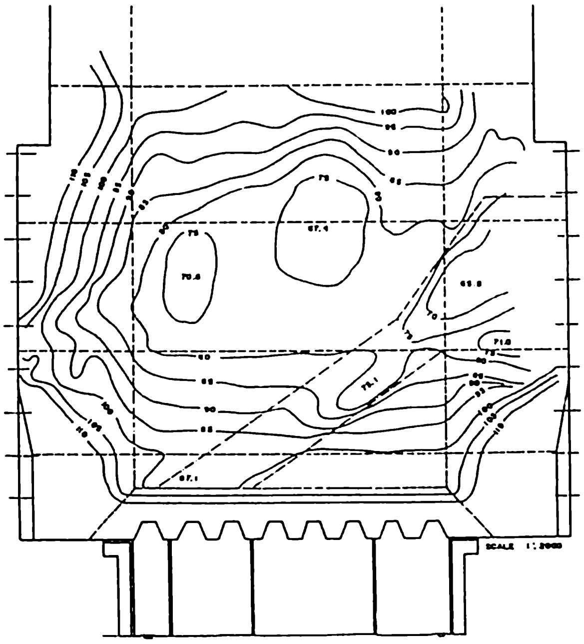


Figure 11. Scour Pattern – Test B1

TEST CONDITIONS :

- NARROW BAND OF WEAK COHESIVE MATERIAL
- ORIFICE SPILLWAY CHUTE CLOSED
- Q = 19600 m^3/s
- RESERVOIR LEVEL = EL. 193 m.
- TEST DURATION = 3 HOURS

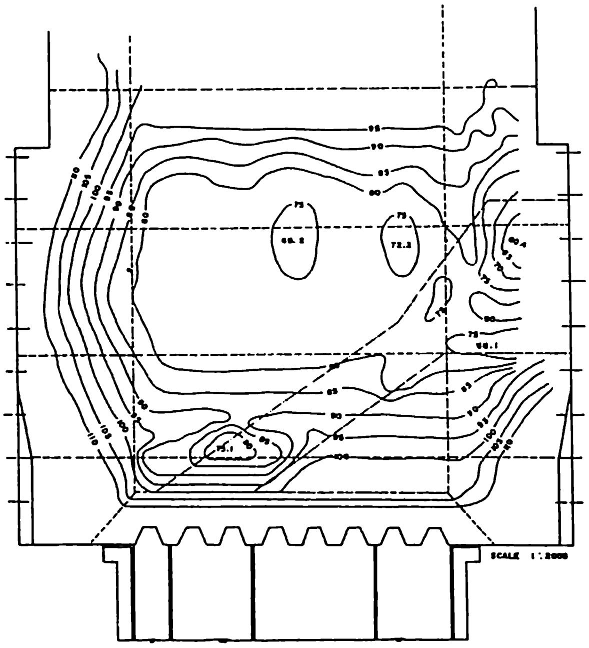
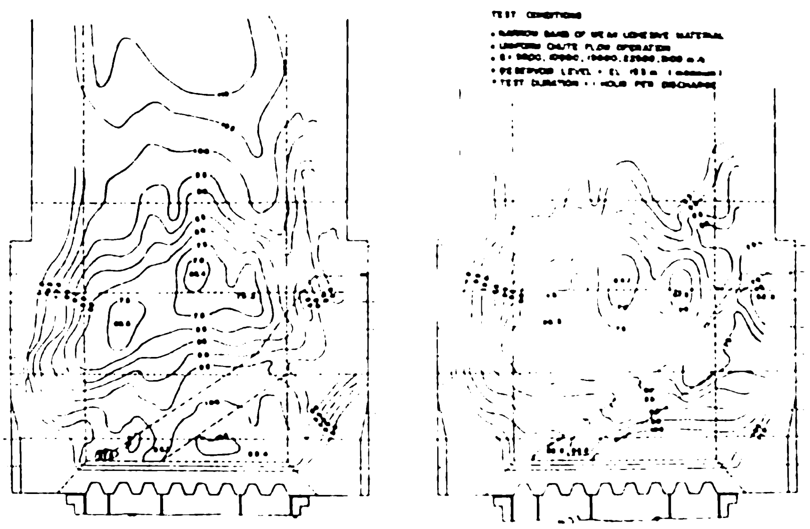


Figure 12. Scour Pattern – Test B2



LOOSE MATERIAL IN PLACE

LOOSE MATERIAL REMOVED

Figure 13. Scour Patterns – Test B4

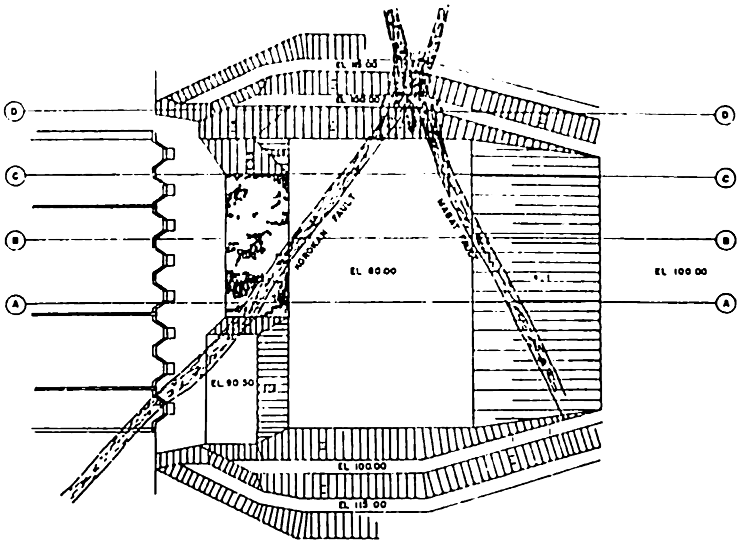
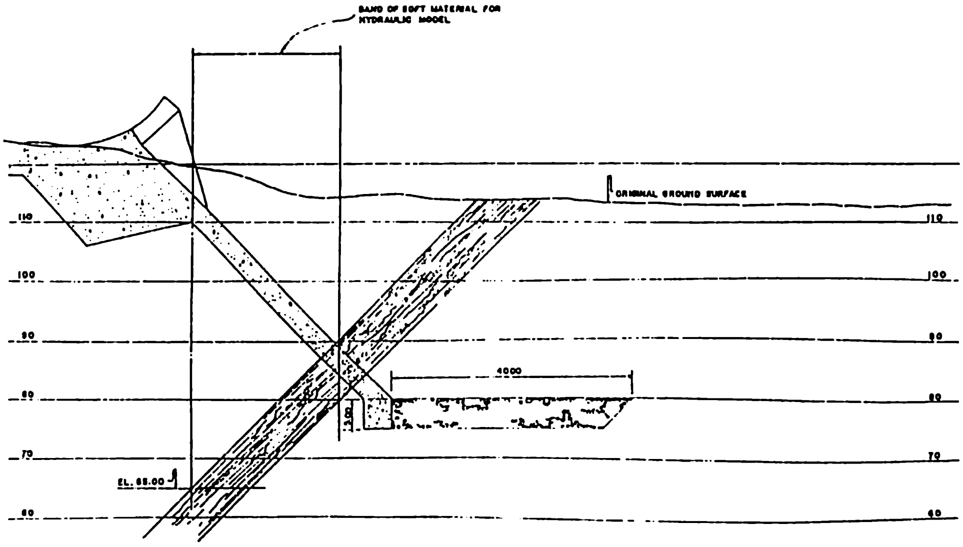


Figure 14. Final toe protection design and plunge pool excavation definition



SECTION ALONG A - A

Figure 15. Longitudinal section through flip bucket and plunge pool : section A-A

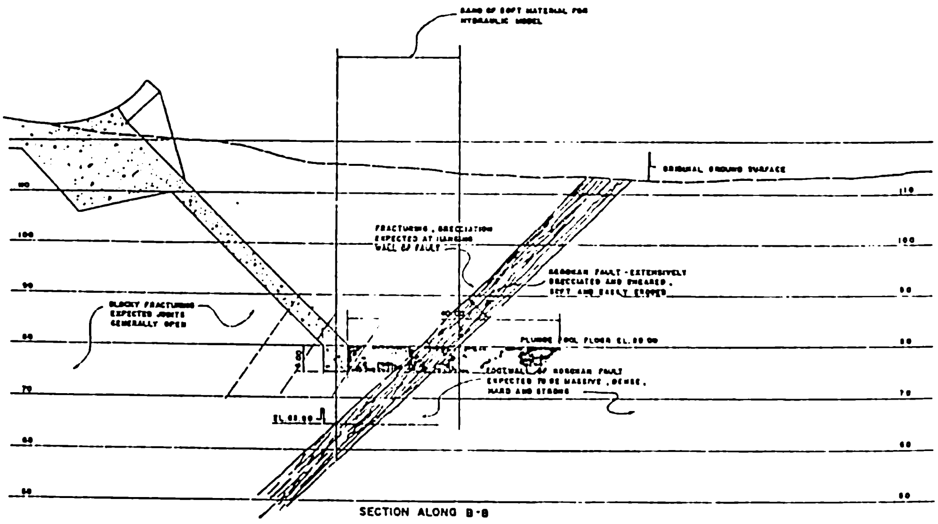


Figure 16. Longitudinal section through flip bucket and plunge pool : section B-B

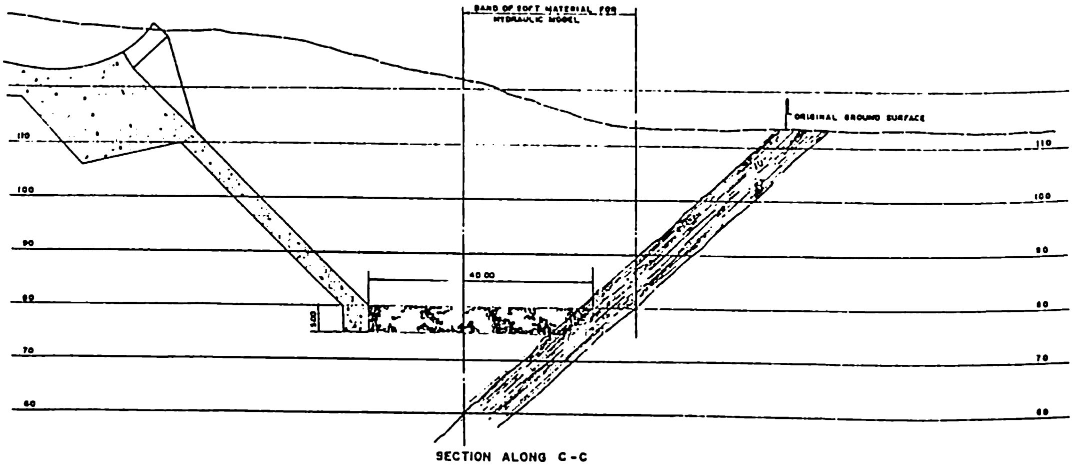


Figure 17. Longitudinal section through flip bucket and plunge pool : section C-C

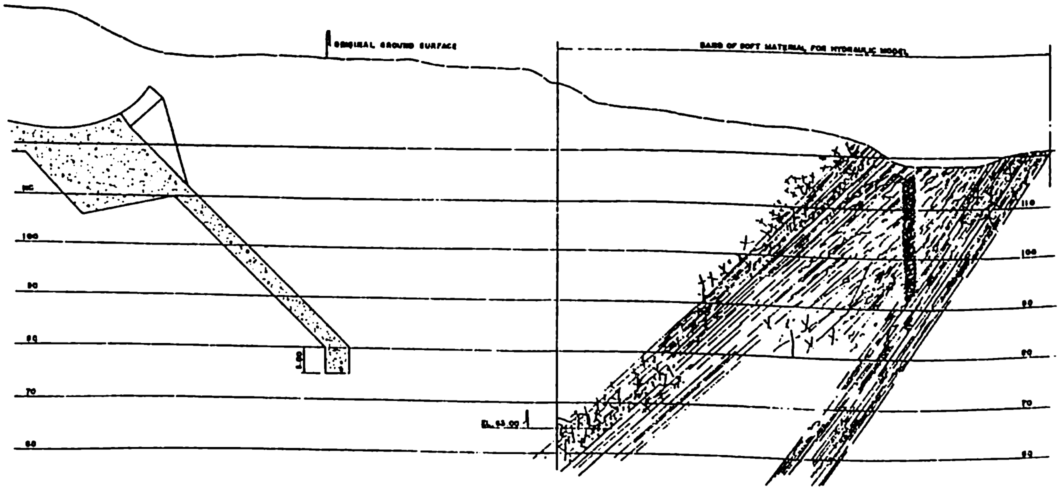


Figure 18. Longitudinal section through flip bucket and plunge pool : section D-D

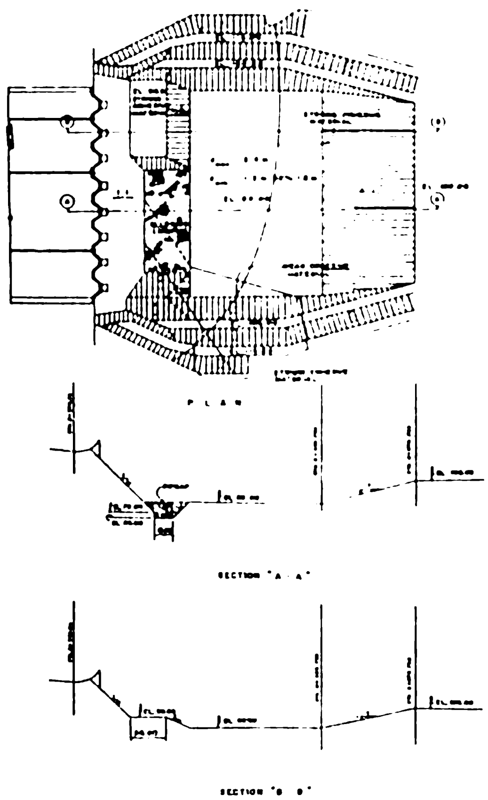


Figure 19. Model representation of plunge pool – final test

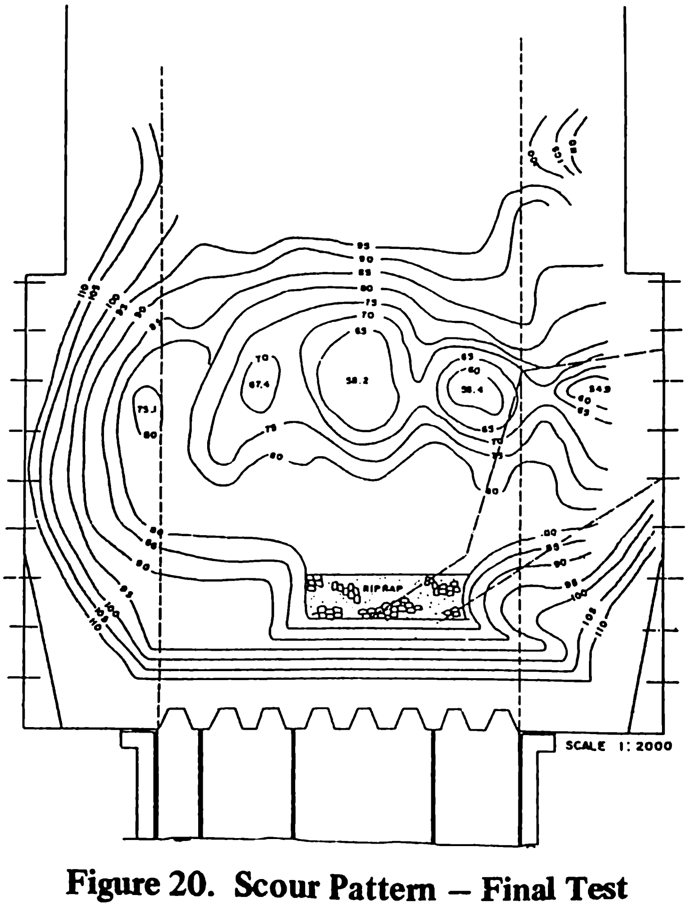


Figure 20. Scour Pattern – Final Test