HYDRAULIC MODEL STUDIES FOR TARBELA DAM

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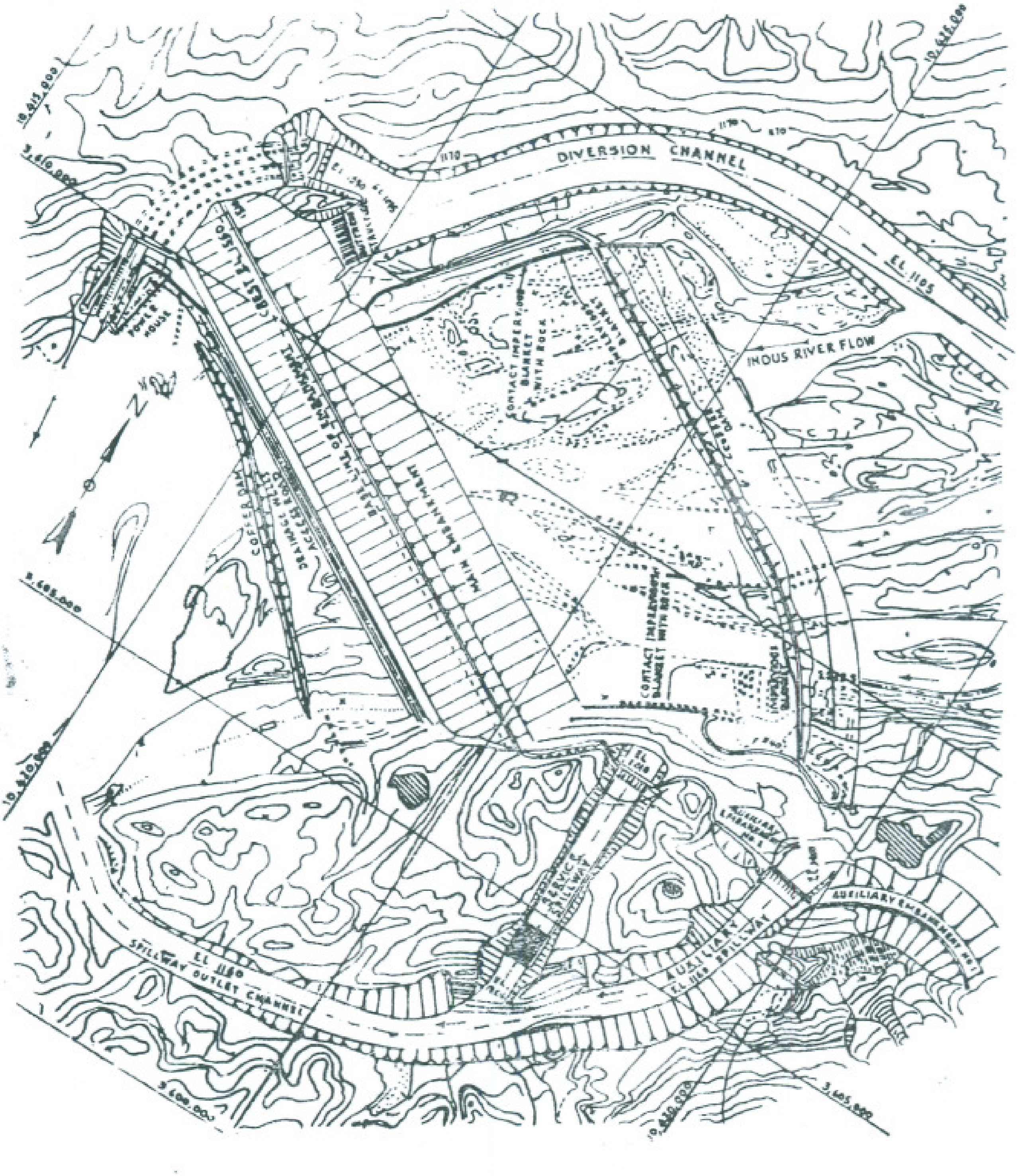
General Description of the Project :

Tarbela Dam embankment, constructed across a 9000 feet wide Indus river valley, is located about 32 miles upstream of the Attock Bridge. It is 450 feet high earth with rock fill dam having a gross storage capacity of 11.1 MAF at an elevation of 1550 and 1.8 MAF at Elevation 1300 which is the minimum assumed draw down level, thus making available 9.3 MAF as the useable capacity. A group of 4 curved tunnels (T_1, T_2, T_3, T_4) in the rock of the right abutment meant to serve initially for river diversion (stage III) and ultimately serve for irrigation releases through tunnels T_3-T_4 and for power generation by utilizing T_1 - T_2 and eventually T_3 are provided. Thus, besides the storage water, the Tarbela Power Plant will provide an ultimate power potential of 2100 megawatts. On the left bank two saddle type spillways (Total spillway capacity 15,00000 cfs) have been cut through the rock of the left bank discharging water through a side valley Dal Dara back to the river. Two auxiliary embankment dams (1) and (2) are constructed to close the upstream end of the side valley (see Figure 1). An impervious blanket in continuation with core of dam covers the river bed to restrict the seepage flow through permeable foundation See Fig. 1 (a). The dam along with its components, could only be completed in minimum of 6 to 7 years and the construction sequences had to be so planned that the normal irrigation supplies and the floods could be passed without damage to the completed works or those under construction. The Tarbela Dam construction in relation to river Indus flows had three distinct stages.

Stage I :	River in natural bed but restricted in plan by construction of coffer dam on right bank.	Approximate period : 2½ years
Stage II :	River in excavated diversion channel on the right bank of River Indus.	3 years.

GENERAL PLAN OF TARBELA DAM PROJECT



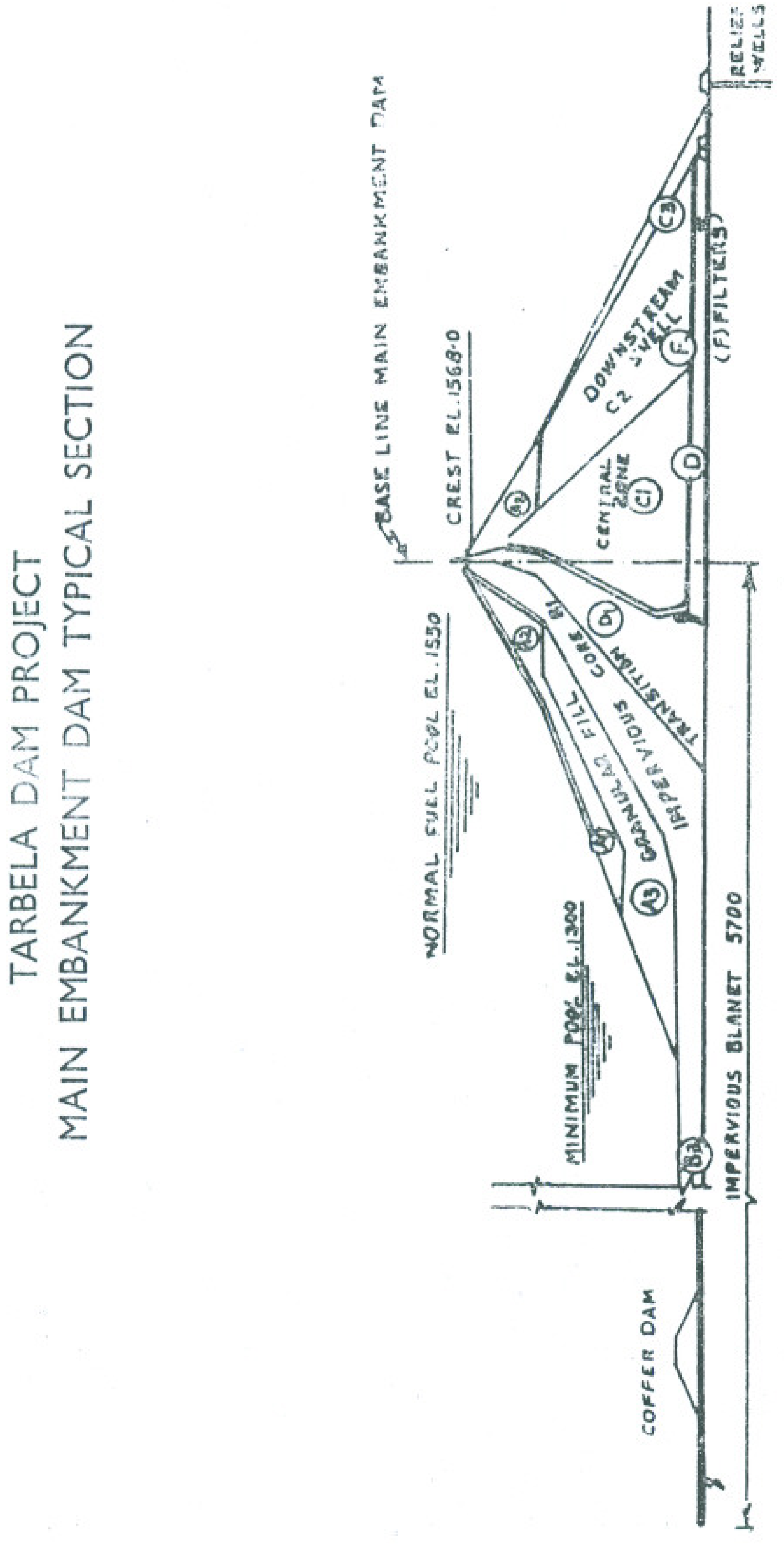

TARBELA DAM PROJECT
MAIN EMBANKMENT DAM TYPICAL SECTION
BASE LINE MAIN EMBANKMENT DAM
CREST EL. 1568·0
NORMAL FULL POOL EL. 1550
MINIMUM POOL EL. 1300
DOWNSTREAM SHELL
CENTRAL ZONE
IMPERVIOUS CORE
GRANULAR FILL
TRANSITION
(F) FILTERS
RELIEF WELLS
IMPERVIOUS BLANKET 5700
COFFER DAM

Fig. 1 (*a*)

Stage III : River diverted through Tunnels. 1 year.

The construction activities during stage I included excavations of diversion channel 650′ wide and about 10,000 feet long, building up of initial sections of the main dam from the material excavated from diversion channel, and construction of gated buttress structure, 27 buttresses at 5 feet each and 28 openings at 20' each—located about 3000' U/S from the tail end of the diversion channel.

In the second stage commenced in Oct. 1970, the river was flowing through the newly excavated diversion channel, while the dam was being constructed between the section completed during first stage and left bank of the valley by using material excavated from spillway channel, tunnels and nearby borrow areas and raising of Stage I, completion of tunnels (including intake area and outlet area works and gate shafts), construction of service spillway, auxiliary spillway, Power House works for unit 1—4, auxiliary dam I and II and auxiliary works such as Coffer Dam C & E.

In the III stage (starting from September 1973), the plug blocking the intake channels of tunnels was removed, buttress gates were closed forcing the river flows through the four channels 1—4 and the final section of the main dam in the diversion channel and right bank contact area was completed.

Investigation and Studies for Tarbela Dam :

For a structure of the size and magnitude of Tarbela Dam, very extensive field data collection and site investigations have to be carried out before any detailed design can be started. The investigation and studies relate to the science of hydrology, geology, foundation Engineering and Soil and Rock Mechanics. For the detailed design the uptodate hydraulic, the structural and mechanical-engineering and scientific knowledge and practices developed in each field have to be pressed into service. The hydraulic model testing is a tool readily available to the design engineer for having an advance glimpse of the hydraulic behaviour of a sructure. The flow conditions, the magnitude and direction of velocities and pressures denoting areas of low pressure and cavitation, the regions of erosion and deposition and the relative merits of different alternative schemes can be studied to adopt the most acceptable alternative, such model studies for each stage of diversion and on each component of the project have to be carried out. At the Irrigation Research Institute, Laboratories at Lahore and Nandipur mainly the studies for stage I and stage II including studies on spillways were taken up. In Colorado State University Laboratory at Fort Collins U.S.A. the hydraulic performance of tunnels 1-4 at stage III diversion was studied. At Alden Laboratories in U›A, further studies on the location and some design features of flow, erosion below spillway, and flow in Dal Dara channel were undertaken.

Inspite of all the hydraulic model studies and field investigations, it is now a known fact that after the completion of the main dam at the time of the first reservoir filling and testing operation, heavy damages occurred in the outlet gate chamber and the stilling basin of tunnel No. 3 and chute of Tunnel No. 4. About 250 feet long section of tunnel No. 2 (downstream of the portal) had collapsed. There was also severe damage in the sides and bed of portal of Tunnel No. 1. The piers of the intake gates of tunnel 1 and 2 had large holes through and through. The cellular coffer dam bounding the power house excavation and forming the left side of outlet areas of tunnel 1 and 2 were toppled over and washed away one after the other. The seepage discharge downstream through the relief wells and drainage ditch was nearly twice that of the computed value. Large sink holes and cracks were noticed in the upstream clay blanket when the reservoir was depleted. Because all these unfortunate events happened inspite of the extensive field investigations and hydraulic model studies, one wonders what is wrong. The failures may be due to geological, hydraulic, mechanical, structural, and maloperational causes, singly or in combination with each other. It is not the purpose of this paper to study and discuss the failure of each component of the project and their possible causes. It is proposed to confine the attention to the hydraulic problems only and to see how the hydraulic model studies have helped in solving the problems. Where the models failed to indicate the true flow picture of the potential danger to the structures were the model results correctly interpreted and recommendations fully utilised or fully or partially ignored in the design ? With the above scope of the paper, the results of the model studies carried out on different aspects of the hydraulic problems and different components of the dam at different laboratories in Pakistan and U.S.A. will be reviewed and summarised, all the time looking for the hydraulic causes of failure that occurred.

After the damage to tunnels 1, 2, 3 and 4 and the stilling basins had occured, more experiments had to be carried out during 1974 and 1975 at the Irrigation Research Institute, and CSU Laboratories at Fort Collins to study the causes of damages and to help in planning the restoration works. These will also be briefly discussed.

A-1.0 Model Experiments for Stage I Diversion.

The Stage-I diversion had the main objective of securing as much working space available in the dam area as was possible by confining the river. During this stage large quantities of material excavated from the diversion channel and the drilling operations of the tunnels was expected to be available to be directly placed to the dam while it was being constructed (thus insuring only one handling) or to be stock-piled in the river area behind the coffer dams. For this reason it was considered necessary to contain the river as much as practicable. The river has a slope 8 feet per mile and the velocities during the floods could be as high as 10 to 12 feet per second. The cofferdam protecting the construction and the stock pile areas would naturally restrict the river bed. The cofferdams have, therefore, to be so located that they present minimum maintenance problems and do not cause unnecessary afflux requiring higher top levels of the cofferdams.

In addition to Stage I cofferdam it was considered necessary that a bridge on river Indus may be constructed prior to the arrival of the general dam contractor so that he could move his equipments without delay to the right bank of the river as soon as the construction work is scheduled to begin. This bridge must therefore, be designed to function properly first without cofferdams and later with Stage I, cofferdam in place. The problems of location, waterway, layout and length of guide banks on the Access Bridge was, therefore, intimately connected with the first stage diversion. The height of the cofferdams would depend on the back water produced by the bridge. Because of the close relationship of cofferdam and the Access Bridge, the experiments and their results on the two studies are reported and discussed together in this appraisal.

The model studies for the above problems were carried out at Nandipur Hydraulic Research Station. Two moveable bed models of the river Indus at Tarbela Dam site, including seven miles of river upstream of the dam site and over 2 miles of river downstream were constructed. The first, the pilot model was constructed to a distorted scale 1/300 horizontal and 1/75 vertical. The second model built to a scale of 1/80 (a geometrical river model) though being large and cumbursome requiring considerable time and work for remodelling the bed and making alterations was the key facility in the comprehensive hydraulic model studies made at Nandipur. The intention was to perform all the proposed tests on the pilot model, reserving the larger one for testing only those schemes which showed promise. The practice adopted, resulted in saving of time and expense.

The river bed on the model was moulded in Haro Sand. It was mainly selected because it has little tendency to form ripples which induce more friction on the model. Boulder bars in the bed of river were duly represented.

At Tarbela site, the river has a braided pattern with three distinct channels. The distribution of flow in the three rivers channels for a total flow of 80,000 was 42.3% in left channel (No. 3) 25.8% in the central channel (No. 2) and 31.9% in right channel (No. 1).

The maximum discharge during 100 years of record at Tarbela is 680,000 cusecs and the minimum is at 15,000 cusecs. The discharge is normally less than 100,000 cusecs from Oct.—March and more than 100,000 cusecs from April to September. A representative hydrograph was selected for the study and the higher discharges were super-posed where necessary.

A-1.1 The Model Results :

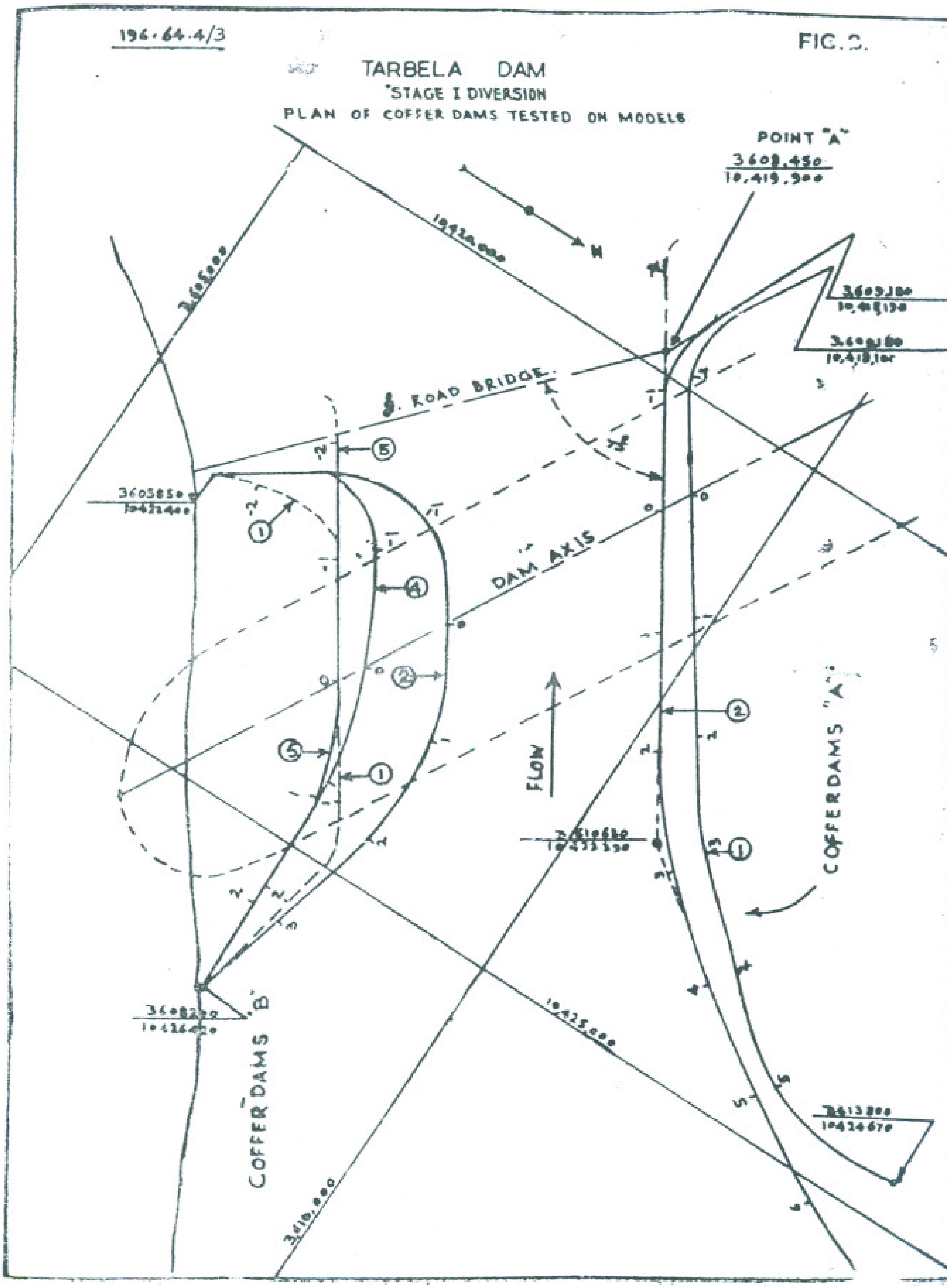
The different positions of the cofferdam (Figure 2) and bridge arrangements as tested on the models are listed in Table 1. For identifying the tests made on the distorted and the geometric models, the suffix D and G is added to the test number to represent the model used. The suffix D stands for distorted and G for geometric model. It was desired to limit the velocities along the cofferdams to 20 ft. per second because for greater velocities, the cost of the protection and maintenance would become excessive.

The first three tests on alignments B1 and B2 of the left cofferdam without any bridge in position, clearly indicated that the left cofferdam would present maintenance problems. For discharges upto about 200,000 cfs, the flow carried by the left channel swings to the right upon approaching the left cofferdam. With the rise in discharge the flow in the left channel impinges upon and severely eroded the upstream end of the cofferdam B2. In these tests velocities ranging up to 29.5 FPS, were observed along the left cofferdam. The cofferdam B2 was, therefore, considered difficult to be maintained whereas cofferdam B1 could be acceptable after modifications of the upstream end.

From further tests it appeared that the cofferdam on the right side could possibly be shifted 200 to 300 feet further to the left to get more storage area. The cofferdam was shifted to position A2 (Figure 2). The difference in the velocity for the two positions was insignificant and the advanced position of the right cofferdam was obviously more suitable because it provided additional storage area on the right bank where it was needed at the expense of loosing some working area on the left side of the river.

In test 5D—G, the cofferdam A—2 in combination with B—4 (Figure 2) was tried. The velocities experienced along the left bank were still higher than 20 fps and, therefore, this change was not considered acceptable.

In all further tests (6D—G to 10—G in Table—1), the Access Bridge was represented in the model. The bridge started at point A and was aligned at 75° with cofferdam A—2 and terminated at the left cofferdam. The downstream end of the cofferdam B—5 served as the approach road for the bridge (Figure 2). At this stage, in the light of the results of tests so far made, it was decided that the working area that could safely


196.64.4/3
FIG. 2.
TARBELA DAM
STAGE I DIVERSION
PLAN OF COFFER DAMS TESTED ON MODELS
POINT "A"
3608,450
10,419,900
N
DAM AXIS
FLOW
COFFERDAMS "A"
COFFERDAMS "B"
10,425,000
3,610,000
3605850
10421400

be protected by a left bank cofferdam would not be commensurate with the cost involved and, therefore, further tests were made with cofferdam A—2 and a bridge spanning the river, but without a cofferdam on the left side. The test 8—G demonstrated the difficulties encountered in trying to eliminate the left cofferdam without lengthening the bridge.

A-1.2 Experiments on Bridge Location, and its Waterway:

The bridge was scheduled to be constructed at least one season before the cofferdam A—2. It is essential that it performed satisfactorily without the cofferdam. In this connection the following problems were sorted out on the distorted model :

1. The best alignment and most economical bridge length for a design discharge of 750,000 cusecs.
2. The span lengths and type of piers.
3. The bridge clearance.
4. The shape and length of guide banks at the abutments for the initial installation without cofferdams.

The tests made are listed in Table II. The principal variable in these tests were the number and arrangement of spans, the type and width of piers, and the alignment, length and shape of guide banks. These factors are listed in Table-II.

The general conclusions and recommendations made as a result of these studies are summarised below:—

1. Without cofferdams, it is necessary to use guide banks on each side.
2. From the tests on the shapes and dimensions of the guide banks (Figure 3), the guide banks labelled as CL at left and BR on the right bank were recommended.
3. The bridge consisting of three spans on right and spanning the winter channel (one span at 200 feet, one span at 400 feet, one span at 200 feet) and 19 spans at 150 feet (out of winter channel) giving a total length of 3270, gave satisfactory performance.

TABLE NO. 1

TARBELA DAM

STAGE I DIVERSION

Record of Model Tests

Cofferdam Arrangements Tested

TEST No.	DIS. CHARGE MAX. c. f. s.	COFFER-DAM No.	BRIDGE ALIGN-MENT	OTHER CONDITIONS
1 D	800,000	A-1		No Bridge
2 D	,,	A-1 & B-1		,,
3 D	,,	A-1 & B-2		,,
4 D-G	,,	A-1		,,
5 D-G	,,	A-1 & B-4		,,
6 D-G	,,	A-1 & B-5	75	Bridge, 26 spans @ 100′=2600′
7 D-G	,,	A-1 & B-5	75	Bridge, 13 spans @ 200′=2600′
8 D-G	,,	A-1	75	Bridge, 17 spans @ 200′=3400′
9 D-G	750,000	A-2	90	Bridge, 19 spans @ 130′, 1@200′, 1@400′, 1@200′ =3270′
10 G	750,000*	A-2	90	Bridge, 19 spans @ 130′, 1@200′, 1@400′, 1@200′, 1@55′=3325′.

* The discharge considered for design is 750,000 Cs.

Table No. 11

TARBELA DAM

STAGE I DIVERSION

RECORD OF MODEL TESTS

Bridge arrangements tested (without Cofferdams)

Test No.	Discharge Max. c. f. s.	Total length ft.	Align-ment Degrees	Bridge Arrangement
11 D	750,000	3400	75	17 spans @ 200′ = 3400′
12 D	,,	3000	75	15 spans @ 200′ = 3000′
13 D	,,	3400	85	14 spans @ 200′, = 1@400′, 1@200′ = 3400′
14 D	,,	3200	85	13 spnns @ 200′, 1@400′, 1@200′ = 3200′
15 D	,,	3450	90	18 spans @ 150′, 1@350′, 1@200′ = 3450′
16 D	,,	3300	90	17 spans @ 150′, 1@200′, 1@350′, 1@200′ = 3300′
17 D	,,	3400	90	20 spans @ 130′, 1@200′, 1@400′, 1@200′ = 3400′
18 D-G	,,	3270	90	19 spans @130′, 1@200′, 1@400′, 1@200′ = 3270′
19 G	,,	3325	90	19 spans @130′, 1@200′, 1@400′, 1@200′ 1@55′ = 3325′

4. The final bridge design (Test No. 190 with the bridge) placed at 90 degrees to the line of cofferdam A-2. when tested with an additional approach span 55 feet in length located to the right of point A (See figure 4) produced no noticeable change in hydraulic performance as the velocities along the cofferdam were well within the limit of 20 fps. In fact there was no difference in the readings of water levels with bridge alone and that with the bridge and the cofferdam.

A-1.3 Stage I Diversion—Prototype Performance.

The design proposal as finalised as a result of model experiments were executed. No abnormal behaviour in the performance or any failure was experienced. The exact comparison of the model and prototype result can not be attempted in this paper. Only the failures or abnormal prototype behaviour are proposed to be discussed wherever these were noticeable.

B—1.0 Model Experiments of Stage II Diversion.

For the second stage diversion of river flow has to be diverted through a temporary diversion channel about 650′ wide at the base, and about 10,000 feet along connecting the river channel on the upstream and downstream of the cofferdam C & E respectively (Fig. 5) enclosing the area for constructing the main dam and also an area for a 10 feet thick clay blanket to be laid in the entire width of the river from the main dam to the upstream cofferdam C. The cofferdam C will rest on the upper edge of the clay blanket. Before the clay blanket is laid and cofferdam C is constructed upon it, it is necessary to divert the flow of the three channels of Indus into the diversion channel by throwing additional cofferdam at suitable place (Fig 5) in the three channels (1, 2 & 3). After this temporary diversion, the laying of the clay blanket under cofferdam C, the construction of cofferdam C and the downstream cofferdam E have to proceed simultaneously. The river closure is the first step and the main feature of the second stage of river diversion.

The river discharge anticipated during river closure scheduled in Oct. 1970 was between 40,000 to 80,000 cusecs as 100 years record indicates that in an average year the river will be flowing at a less than 80,000 cusecs for approximately 240 days.

During the period 1868 to 1964 the discharge exceeded or equalled 80,000 cusecs in the month of October. In November only once in this period the discharge had exceeded 80,000 cfs. (It was 200,000 at Darband and about 230,000 cfs at Tarbela in the 3rd week of November) so discharge of 80,000 cfs at Tarbela during October and in November is taken as the most probable upper limit of the discharge for diversion, the incidence cf higher discharge was, however, not ruled out.

The stage II hydraulic problems for model investigation are:—

(*i*) River diversion into diversion channel.

(*ii*) The flow through the diversion channel and the Buttress structure.

(*iii*) The flow downstream of the buttress structure.

(*iv*) The flow along coffer dam C.

B-1.1 Results of Experiments on River Diversion into the Diversion Channel.

The problems which have to be settled and needed attention were:—

(*i*) The best position of the temporary closure dams in the three channels.

(*ii*) The best and most economical sequence of closure of the three channels for easy diversion.

(*iii*) Effect of removal or otherwise of the shoal in front of the mouth of the diversion channel on the diversion operation.

(*iv*) The most economical procedure of closure in the matter of time and consumption of materials of various sizes.

(*v*) To assess the water levels likely to be generated above and below the closure dams.

B-1.2 The best position of the temporary closure bunds in the three channels

The points to be kept in view in selecting the temporary closure dam sites are:—

(*a*) The closure dam should be at a small distance below the bifurcation point of the two channels, so that when closure is affected the rejected discharge found easy access to alternate course with the minimum afflux at the bifurcation point.

(*b*) The ends of the cofferdams could be joined to high lands on the two sides to avoid by passing through ends immediately after the closure is affected.

(*c*) It is not placed in the regions of rapids and areas of near critical flow conditions.

B-1.3 The best and most economical sequence of closure of the three channels for Easy Diversion.

To investigate the best procedure for closing the three river channels series of tests were conducted on 1/80 natural scale model of River Indus at the Hydraulic Research Station, Nandipur in 1963-64. On the basis of these tests the following procedure of river closure was recommended by M/S TAMS who are responsible for designing the project.

(1) Remove plug, allowing the diversion channel to go into operation.

(2) Construct closure dam across right channel.

(3) Equipment can now be moved into the river bed and the diversion channel portion in the river bed from station 0+00 to 20+00 may be excavated.

(4) Close the central channel.

(5) Close the left channel last of all.

An actual closure was being materialized six years after the above testing. T. J. V. Contractors for Tarbela Dam again requested Irrigation Research Institute, Lahore on 1-1-1970 to set up a 1/60 natural scale model of River Indus for more detailed study relating to river diversion at Tarbela.

Simultaneously Sogresh Hydraulic Laboratory in Grenoble was asked to carry out flume tests to determine the grain size of the material to be used for closure on the basis of water levels observed on Nandipur model in 1964 and to compare different closure methods to find which is the most suitable for Tarbela site.

A model representing more than 20,000 feet stretch of river Indus located between a point some distance upstream of the trifurcation point of three channels and a point downstream of the outlet of diversion channel into the river, was constructed on 1/60 natural scale. The model river upstream of the main dam axis was moulded to conform to contour supplied by T. J. V. while lower down it was moulded to 1968 cross sections supplied by TAMS. The river bed upstream of the trifurcation point was moulded in accordance with 1964 curve.

The river bed on the model was moulded in Haro Sand specially arranged to simulate the prototype range of the river bed material.

Sequence of Closure of the 3 River Channels :

In this test series the diversion channel was opened at its intake located just D/S of old Pehur canal head regulator hillock on right bank of the right channel without excavating its portion between station 0+00 to 20+00 in the river bed. Following four sequences of closure :

Right	Centre	Left
Right	Left	Centre
Left	Centre	Right
Left	Right	Centre.

were model-tested for river discharges 40,000, 60,000 and 80,000 cusecs. From the model it was observed that :

(*a*) As the plug in the diversion channel is removed, the maximum drop in water level is in the right channel whereas the drop in water level in the central and left channel is insignificant.

(*b*) Closure of the right and central channels does not affect the water levels in left channel significantly as the backwater effect just reaches the off-take point of left channel.

(*c*) Initial closure of left channel alone results in rise of water level in the central channel by 3.6, 3.9 and 4.5 feet at respective discharge of 40,000, 60,000 and 80,000 cusecs whereas the corresponding rise in the right channel is 2.7, 1.4 and 1.7 feet.

(*d*) Closure of left and central channels results in rise of water level in the right channel by 3.3, 3.6 and 4 3 feet at river discharges of 40,000, 60,000 and 80,000 cusecs.

(*e*) The combined effect of closure of the right and left channels is that the water level in the central channel rises by about 4 feet at the three specific discharges.

(*f*) The stabilized water levels at site of closure dams when the three channels are closed is independent of sequence of closure of the 3 channels.

Excavation of Approach to Diversion Channel :

In this set of tests the approach to diversion channel was widened and deepened *i.e.* diversion channel in river bed from 0+00 to 20+00 was excavated. In the first test right channel was closed and the model was run for the selected discharges of 40,000, 60,000 and 80,000 cusecs. The water levels at the 3 closure dams sites were recorded. In the second test central channel was also closed and the water levels were again observed at the closure dam sites. In the last test left channel was also closed along with right and central channels and water levels recorded at the three closure dam sites.

A comparison of water levels at the three closure dam sites with closure of different channels, with and without excavation of diversion channel between station 0+00 to 20+00 in the river bed showed that with the excavation of diversion channel between station 0+00 to 20+00 the water levels in the central channel get lowered substantially. The water level in the central channel at its offtake point drops by 2 to 2.7 feet, with the closure of right and left channels, 3 to 3.6 feet with closure of right and central and 2.9 to 4.5 with closure dam in all the three channels. Water levels of right channel at closure dam site drop by 0.5 to 1.0 feet whereas the drop in water level in the left channel is insignificant and so widening and deepening of approach channel was not recommended.

B-1.4 Grade and Dumping Rate of Material to be used for Closure :

Sogreah (France) made some erosion tests by using stones of different grades in the closure dam and maintaining different constant head drops in the gap between advancing head of the closure dam and stone protected opposite bank. The head drop was varied from 1 to 8.3 meters which was the maximum head drop recorded on 1/80 scale Nandipur model. From these tests Sogreah recommended the following three grades to be used for river closure at Tarbela.

Grade I	=	River bed material.
Grade II	=	Stone of 80 to 400 lbs.
Grade III	=	Rock not less than 1100 lbs. 50% more than 2200 lbs.

The rate and procedure of dumping the material as planned by TJV was:

Grades II & III were always to be placed in conjunction with Grade I. Grade I & II and similarly Grade I and III were dumped in ratio of 2/3 & 1/3 respectively. The crest width of the three closure dams was fixed as 95 feet to allow turning manoeurs of earth moving machinery. The initial crest levels of the three closure dams were kept 1.5 feet above the water levels recorded on the model—

B-1.5 Technique of river closure

Having decided the sequence of closure of the three river channels and the site of the closure dams (in view of site conditions especially rapids in three channels d/s of three off take points) next problem was to investigate the most suitable method and technique of closure. From a number of quick tests conducted at Sogreah it was recommended to protect 500 feet length of the left banks of three channels opposite to closure areas and the closure dams to be aligned to follow a shape of hockey stick. This shape was tested along with other shapes on 1/60 scale comprehensive model at Nandipur.

Hockey stick shape closure dams

The model was remoulded to 1969 survey and the left banks of the three channels against which closure was to be made were protected by grade III rock fill for a length of 500 feet and a thickness of 20 feet at the toe of the bank. The model was run for 80,000 cusecs, the diversion channel was opened and when the flow was stabilised, the closure in the right channel was started by dumping grade I material from the right bank of the channel in a way so that the upstream crest edge of the closure dam was in line with the upstream edge of the stone protection on the opposite bank. The dam was advanced in a straight line till the gap width was 220 feet, then axis of the dam was deflected downstream with continued downward inclination to follow the shape of hockey stick (see Fig. 6). The dumping of grade I material was continued with the specific rate of 1000 cub. yd/hour till the erosion at advancing head of closure dam as well as of the channel bed was excessive and compatible with rate of dumped material and the rate of rise of water level got slackened. At this stage grade II material was introduced. Grade II material was placed at the upstream advancing edge of the closure dam while the remaining portion of closure dam was built by dumping grade I material. The rate of dumping grade II material was half of rate of dumping of grade I material. Water levels generated upstream and downstream of the advancing dam were measured at regular intervals throughout the closure operation. The volume of the material dumped, increment in the dam length as well as the scour at the advancing head of the dam was recorded at fixed intervals. The above test was repeated as assuming that diversion channel is plugged at its entrance point.

After closing the right channel, central channel was also closed in the manner described above. In this case also model data regarding time of closure, quantity of material and water levels upstream and downstream of the closure mound was collected.

After closing the right channel, central channel, closure of left channel was started in a way detailed for closure of the right channel. In this case due to more concentrated per foot run discharge and more head drop, placing of grade I material in the wake of grade II was a bit difficult, so the front of u/s advancing

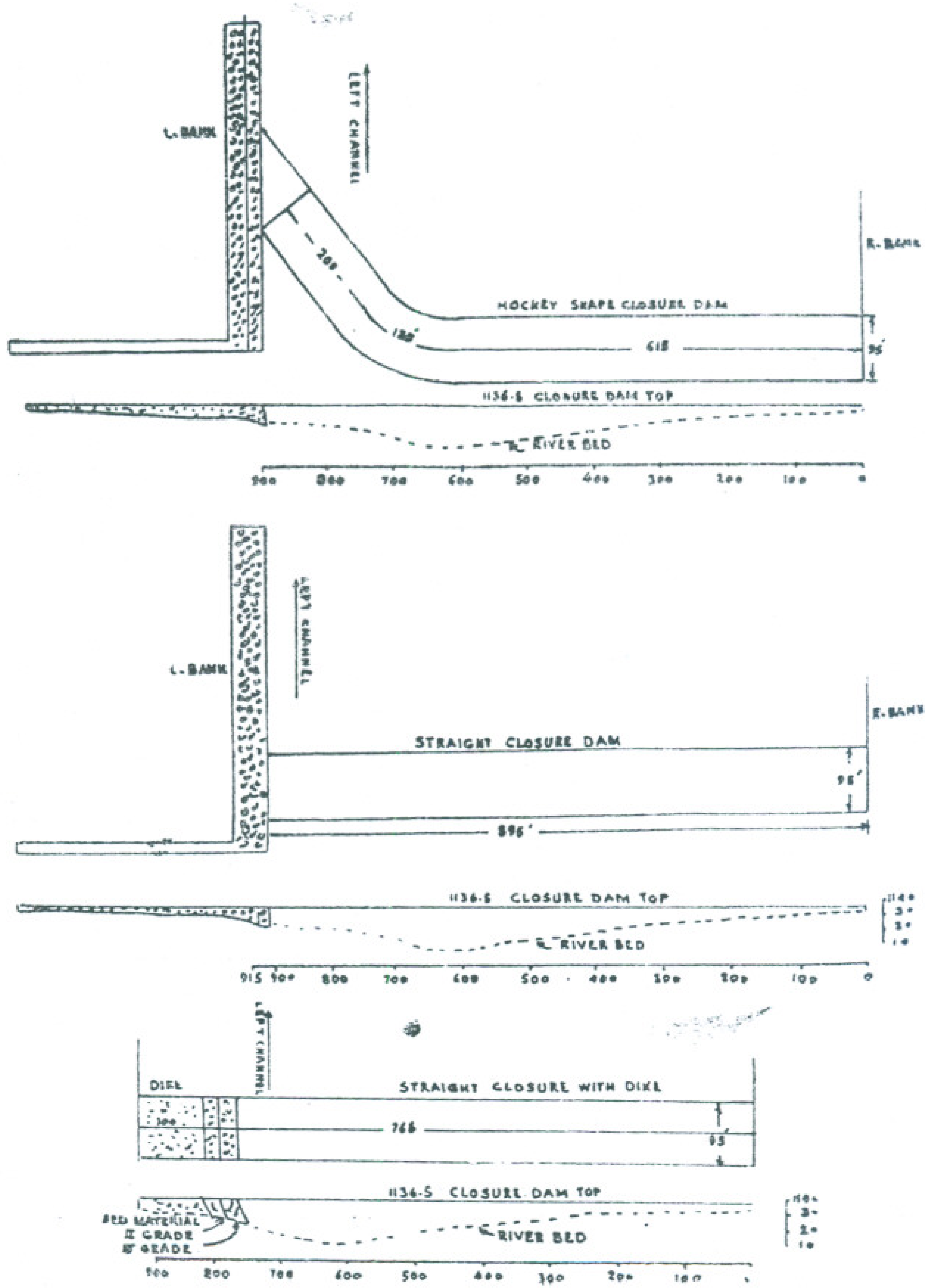
TARBELA RIVER CLOSURE MODEL

SCALE = 1/60

DIFFERENT SHAPES OF CLOSURE DAM

FOR LEFT CHANNEL

TESTED ON THE MODEL



spur head built by tipping grade II material had to be be kept about 30 to 40 feet in advance of the grade I front. In case of grade III material due to high head drop and big void ratio in the rockfill the excessive percolation in grade III made the placement of grade I material at the back of grade III material difficult and so impervious material had to be dumped on the upstream face of the advancing head of the rockfill. It was observed that when the scour at the advancing head of grade II material becomes excessive the stone removed by high velocity jetting flow goes into scour and paved its bed. Advancing of head of closure dam gets accelerated when the scour hole gets paved up with grade II material. At a certain stage of progression of advancing head of closure dam, the scour becomes larger in depth and extent and the velocity of the diverging flow becomes so excessive that the material which goes into scour does not stay there and is moved out of scour and deposits lower down where the flow diverges out and so at this stage a great percentage of grade II material instead of paving the scour paves the river bed lower down and this is signal for start of dumping of grade III material.

The time taken for closures, the quantity of material dumped, the water levels generated upstream and downstream of the embankment were also recorded.

Straight closure dam

The bed of the diversion channel being at lower elevation than the bed of the right channel, it was observed that when the diversion channel is opened it draws major portion of the right channel discharge and hence in this case a straight closure dam can be raised without any trouble. Similarly the discharge in the central channel being small here also a closure dam could be advanced in straight line. In this test series, therefore, straight closures were attempted on all the 3 river channels. The model data for the three channels was recorded and have been compared with the data of hockey shape closure dam in Table below which show that straight closure in right and central channel is possible but at left channel it means more wastage of material as it was noticed that hockey alignment of Coffer Dam follows the deep scour alignment and so no extra stone was required to pave or fill the scour hole as in case of straight alignment.

Test with dike projecting out from left bank

In this test the stone protection on the left bank of channel was removed and 150 feet long dike on alignment of straight closure dam with 95 feet top width, projecting straight from the left bank of the left channel was constructed before starting the closure. The first 100 feet length of this dike was in river bed material followed by 20 feet length of grade II material and ending in grade III rockfill for a length of 30 feet.

The right and central channel were closed beforehand, the diversion channel was opened and the model was run for 80,000 cusecs river discharge. When the water levels in all the channels stabilished, closure was started in the last channel by dumping grade I material from the right bank in a way that the axis of closure dam and axis of dike fall in a straight line. The closure dam progressed towards left in the manner described above. The model data regarding time, quantity of material and water levels is compared with the hockey shape and straight closure in Table III.

TABLE III

TARBELA RIVER CLOSURE MODEL

Table showing closure time and quantities of material dumped for different shapes of closure dam in channel No. 3.

Serial No.	Shape of closure dam	Dam length in ft	Closure time in hours	Quantity of material in cubic yards				
				Grade I	Grade II	Grade III in cl : dam	Grade III on bank	Total
1.	Hockey Stick.	242	86	96000	19000	11500	15000	141500
2.	Straight	895	90	93000	23000	7000	15000	136000
3-A	Straight	765	66	67000	80000	12500	...	87500
3-B	Dike	150	14.5	4500	1500	2000	...	8000
	3A+3B :	915	80.5	71500	9500	14500	...	95500

Note :

(i) In No. 2 (Straight closure dam) 2500 cub yards of Grade III Material dumped from top to maintain bank protection on left bank.

(ii) In No. 3 (closure with dike) 1000 cub. yards of Grade III material dumped from top to maintain head of the dike.

Three selected discharges are tabulated below.

Closure dam in right channel (diversion channel kept closed).

River discharge in c. f. s.	Upstream Water level	Downstream Water level
40,000	1126.2	1110.0
60,000	1128.0	1112.6
80,000	1129.0	1114.1

Closure dam in central channel (diversion channel open).

River discharge in c. f. s.	Upstream Water level	Downstream Water level
40,000	1123.5	Bed level
60,000	1125.0	1114.4
80,000	1126.0	1116.1

Closure dam in left channel (diversion channel open).

River discharge in c. f. s.	Upstream Water level	Downstream Water level
40,000	1130.3	...
60,000	1132.8	...
80,000	1135.0	...

The total quantity of material required for each of the closure dams in straight closure with left bank dike as measured from the model is :—

Right channel	...	52500 cubic yards.
Central channel	...	30500 cubic yards.
Left channel	...	95500 cubic yards.

B-1.6 Conclusion from 1970 Model Tests.

From the model tests conducted at Nandipur and Sagrial the conclusion arrived at from the hydraulic standpoint are as follows ;

1. The plugs at the upstream and downstream ends of the diversion channel be removed in toto.

2. The excavation of the portion of diversion in the river bed did not give any added advantage in closure of left channel where final closure is to be effected.

3. The three grades required for effecting the closure are ;—

(i) River bed material.

(ii) 80 to 400 lbs stone.

(iii) Heavy stones between 1100-2200 lbs.

4. The closure to proceed from right to left in sequence of right, centre and left channels.

5. The banks (opposite to closure dams for channel left and middle) protected with heavy rockfill for a length of 500 feet at site act as rigid barriers.

6. The closure dams to be aligned straight.

7. A dike with sloping nose (preferably at 1 : 4 of about 150 feet length projecting straight from the bank opposite to closure dam may be provided on the left channel.

B-2 River Diversion at Site.

River diversion at site was initially planned according to model findings. The removel of upstream and downstream plugs of the diversion channel was started on 15th September 1970. Unexpectedly a 20 feet thick layer of mud stone was encountered in the plug at entrance of diversion channel which could not be removed with a drag line. It had either to be blasted or removed completely with showels in dry. Since the blasting was estimated to take more time than available planned, sequence of events had to be modified for removal of plug in dry, by the closure of the right river channel with closure dam 1-a downstream and with closure dam 1-b upstream of the mouth of the diversion channel.

B-2.1 Closuse of right Channel.

The construction of closure dam 1-a started on the 14th of September, the total discharge of the river Indus decreased during closure from 63,300 cubic feet per second to 60,300 cubic feet per second. The partial discharge in the channel to be closed was 20,000 cubic feet per second. The opposite bank was protected prior to closure by a length of 500 feet with 11,500 cubic yards heavy boulders. The water level upstream of the closure dam rose from EL. 1120.0 to EL. 1129.7 by 9.7 feet. The water level downstream of the closure dam fell from El. 1120,0 to EL. 1113.3 by 6.7 feet. The head drop was 16.4

feet. The width of the closure dam measured 95 feet on the crest, the crest elevation measured at EL. 1130.5 and the length was 400 feet, 69,900 cubic yards rock and 3,600 cubic yards of heavy boulders between 1,100 lbs, 2,200 lbs. were used for the closure. Approximately 30% of the dumped material was washed away because the river bed material consisting of boulder gravel sand contained approximately 15-20% fine materials smaller than 0.15".

Furthermore, impervious material was dumped at the upsteam face of the closure dam to increase the water tightness. The maximum dumping rate was 2600 cubic yards and the closure took 33 hours. After completion the height of the closure dam was increased on a width of 30 feet to a level safe against overtopping due to a flood with the discharge of 170,000 cubic feet per second. Thereafter closure dam I-a was extended across the island to the middle river channel with cofferdam I-c safe against the above flood.

The next stop in the operations of diversion was the construction of closure dam I-b upstream of the mouth of the diversion channel in still water, for which 60,000 cubic yards rocks as excavated were used.

After completion of closure dam I-b the closure dam I-a was breached to dewater the area between the closure dams I-a and I-b in front of the upstream plug of the diversion channel. The water level fell from EL. 1129.7 to EL 1111.4 by 18.3 feet.

The removal of the upstream plug was completed on the 3rd of October.

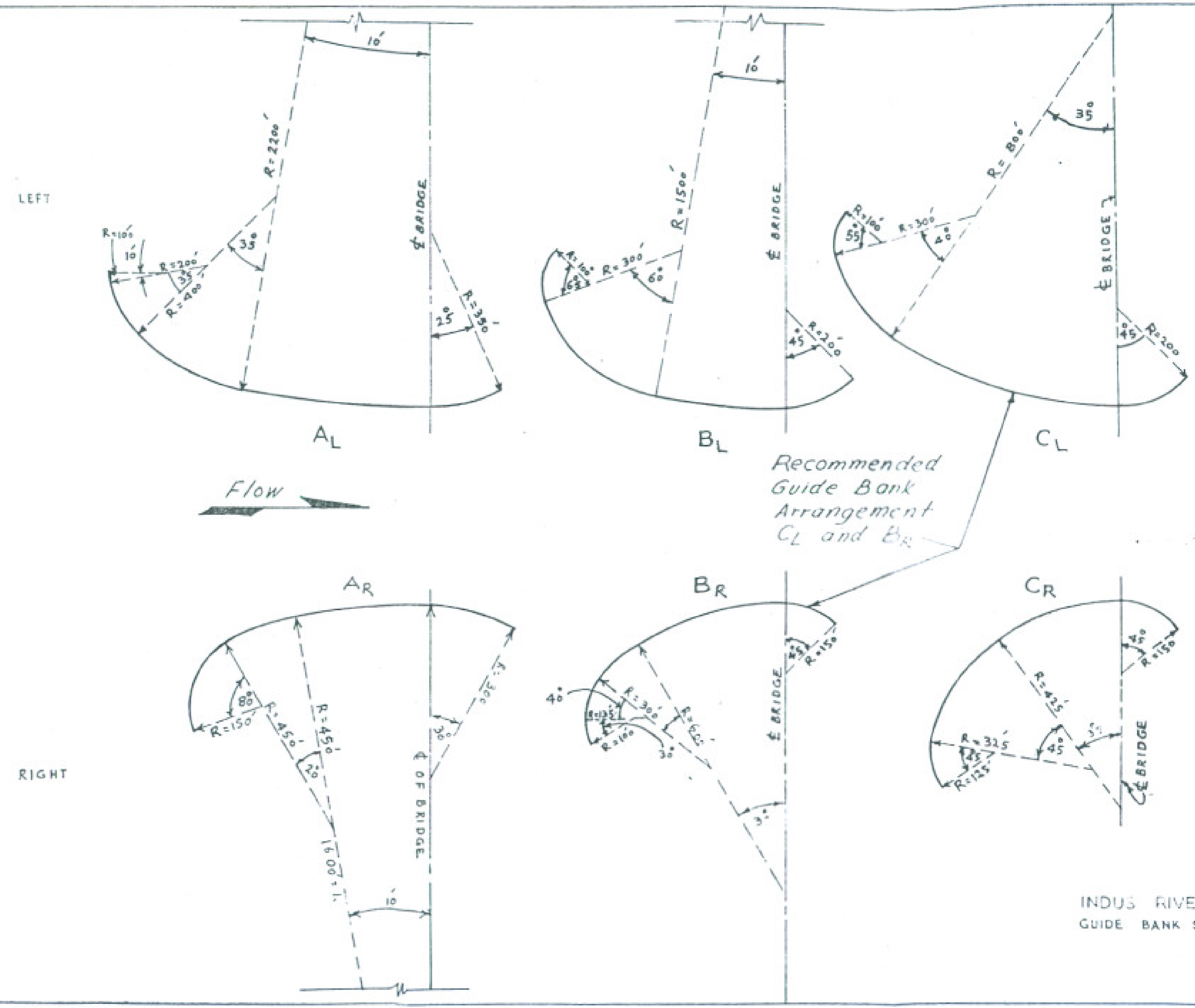
For opening the diversion channel a total quantity of 650,000 cubic yards had to be removed within 3 weeks.

On the 5th of October the diversion channel was flooded by breaching closure dam I-b with dozers after closing the breach in closure dam I-a.

B-2.2 Closure of Middle Channel

Starting from evening of 5th October the closure took 18 hours. During closure the total discharge of the river Indus increased from 58,000 cubic feet per second to 90,000 cubic

FIG NO. 3.



INDUS RIVER BRIDGE
GUIDE BANK SHAPES TESTED.

FIG. 4

TARBELA DAM PROJECT
DETAILS OF INDUS BRIDGE
STAGE-I DIVERSION

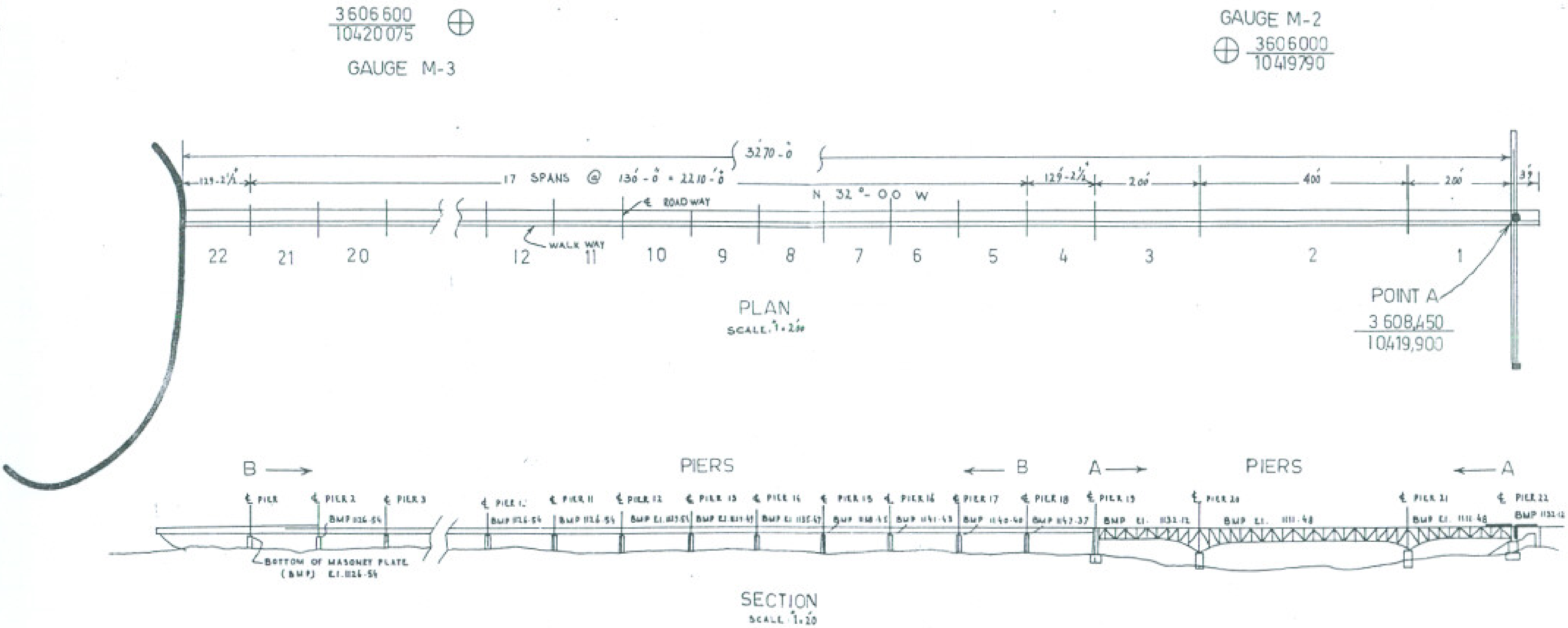
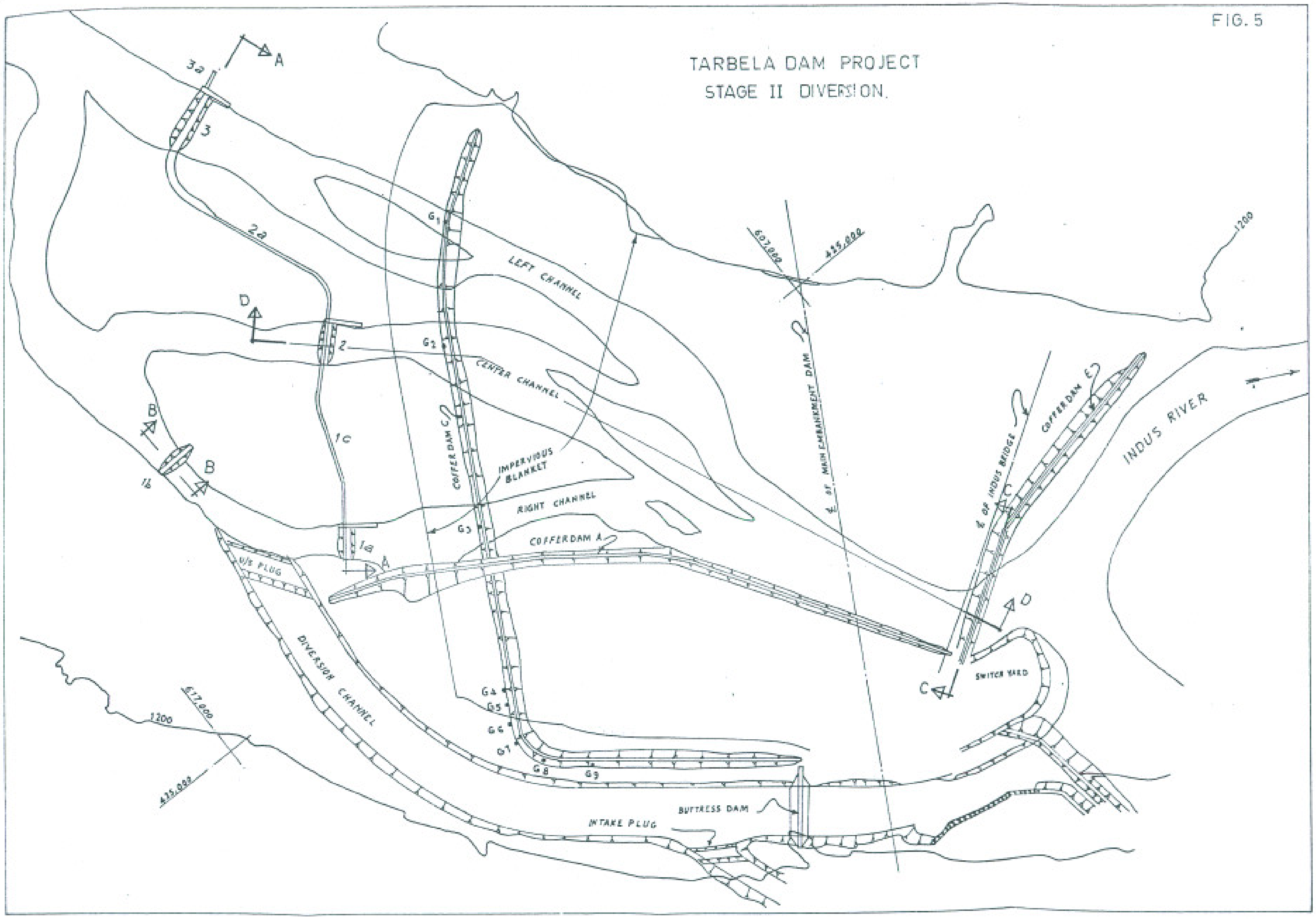
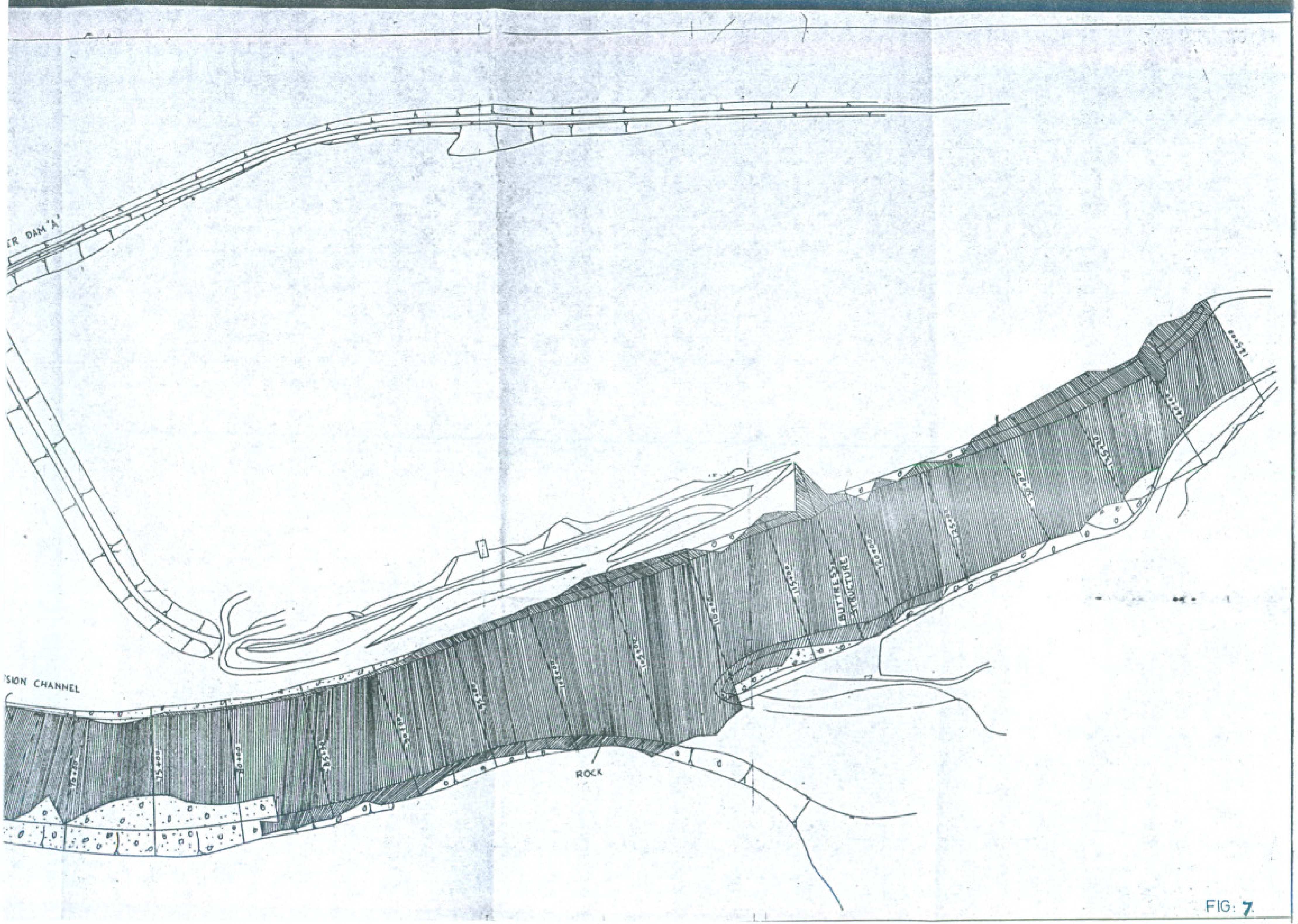


FIG. 5

TARBELA DAM PROJECT
STAGE II DIVERSION.





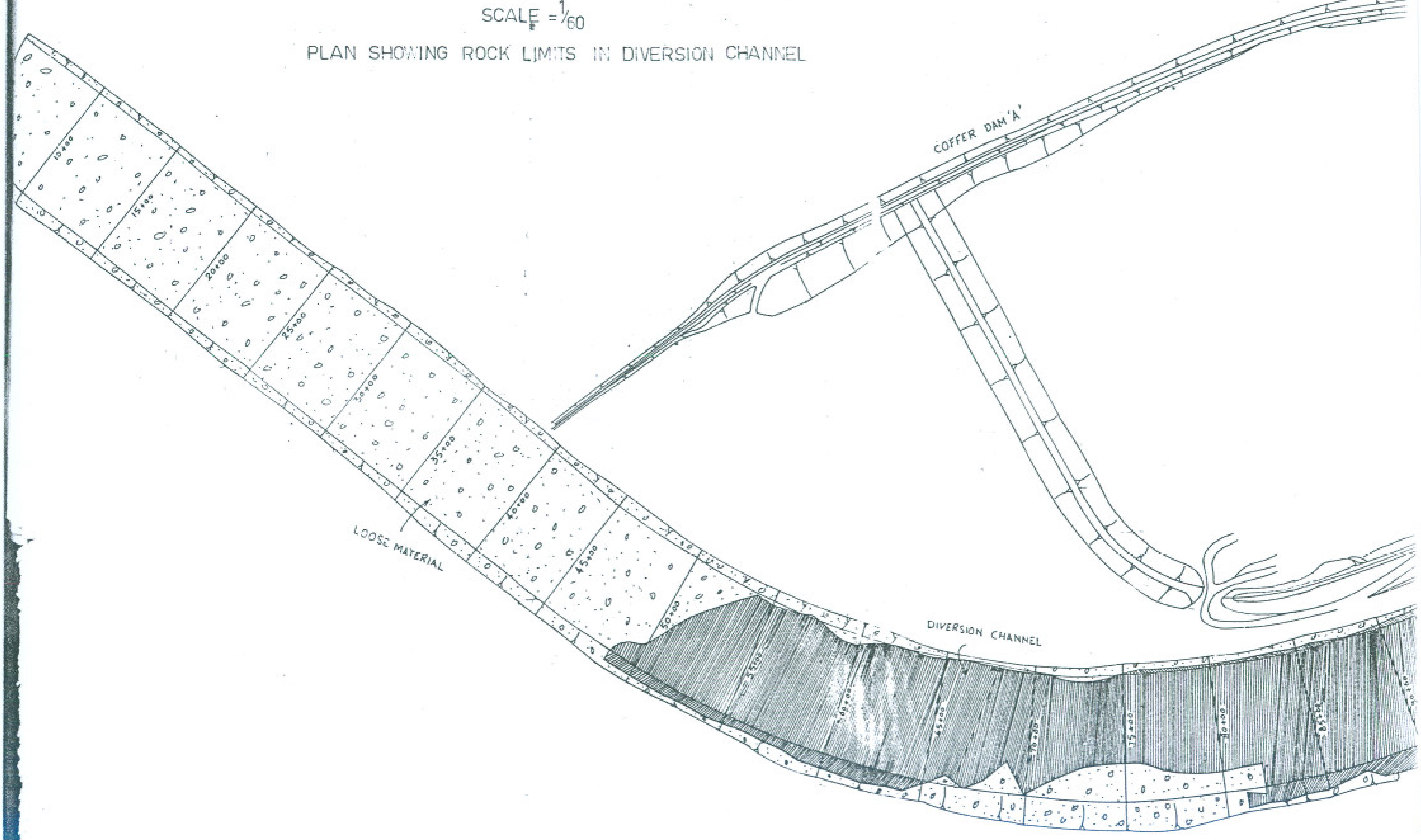
ER DAM 'A'
SION CHANNEL
ROCK
BUTTRESS STRUCTURE
70+00
75+00
80+00
85+00
90+00
95+00
100+00
105+00
110+00
115+00
120+00
125+00
130+00
135+00
140+00
145+00

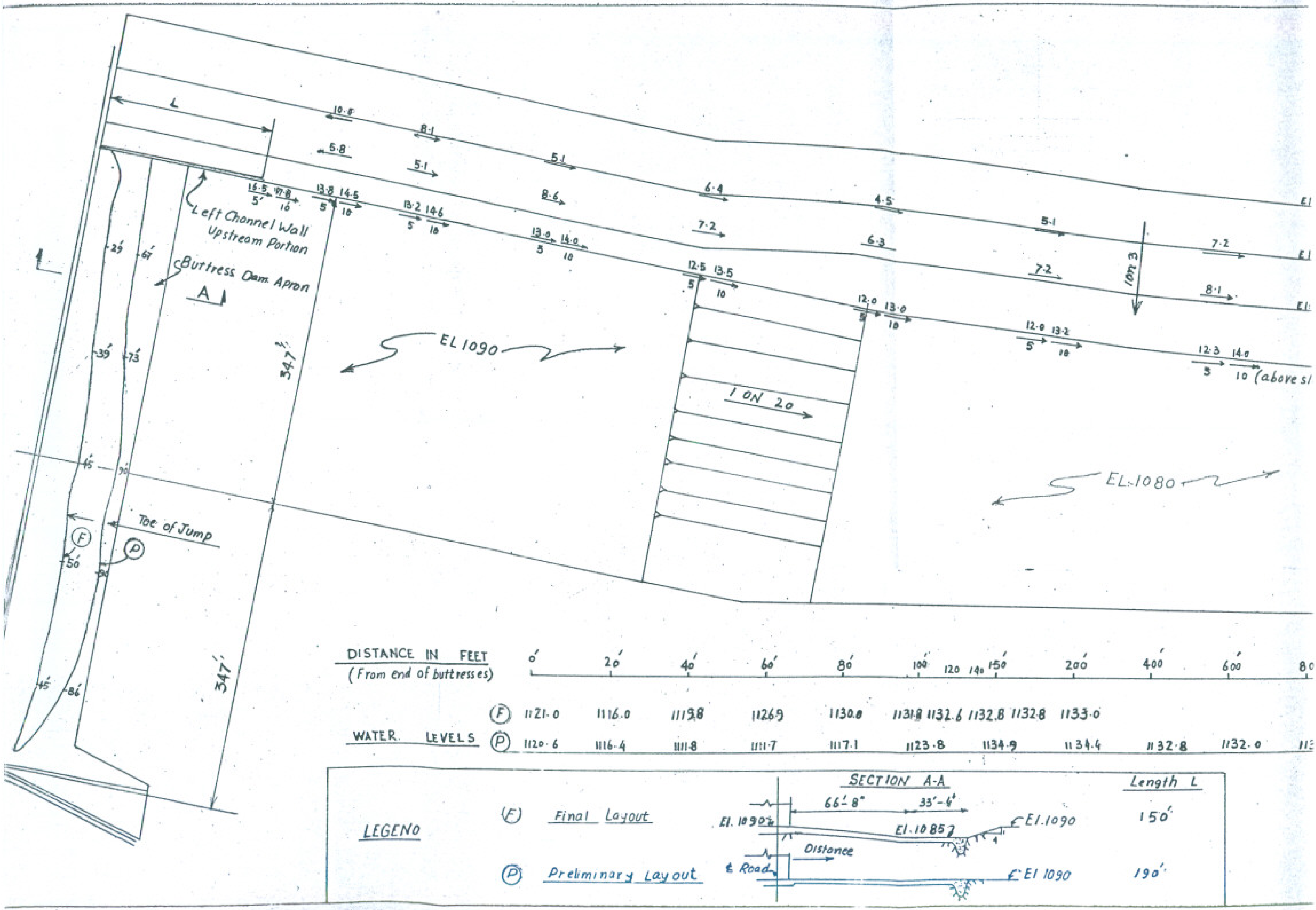
FIG: 7

TARBELA RIVER CLOSURE MODEL

SCALE = 1/60

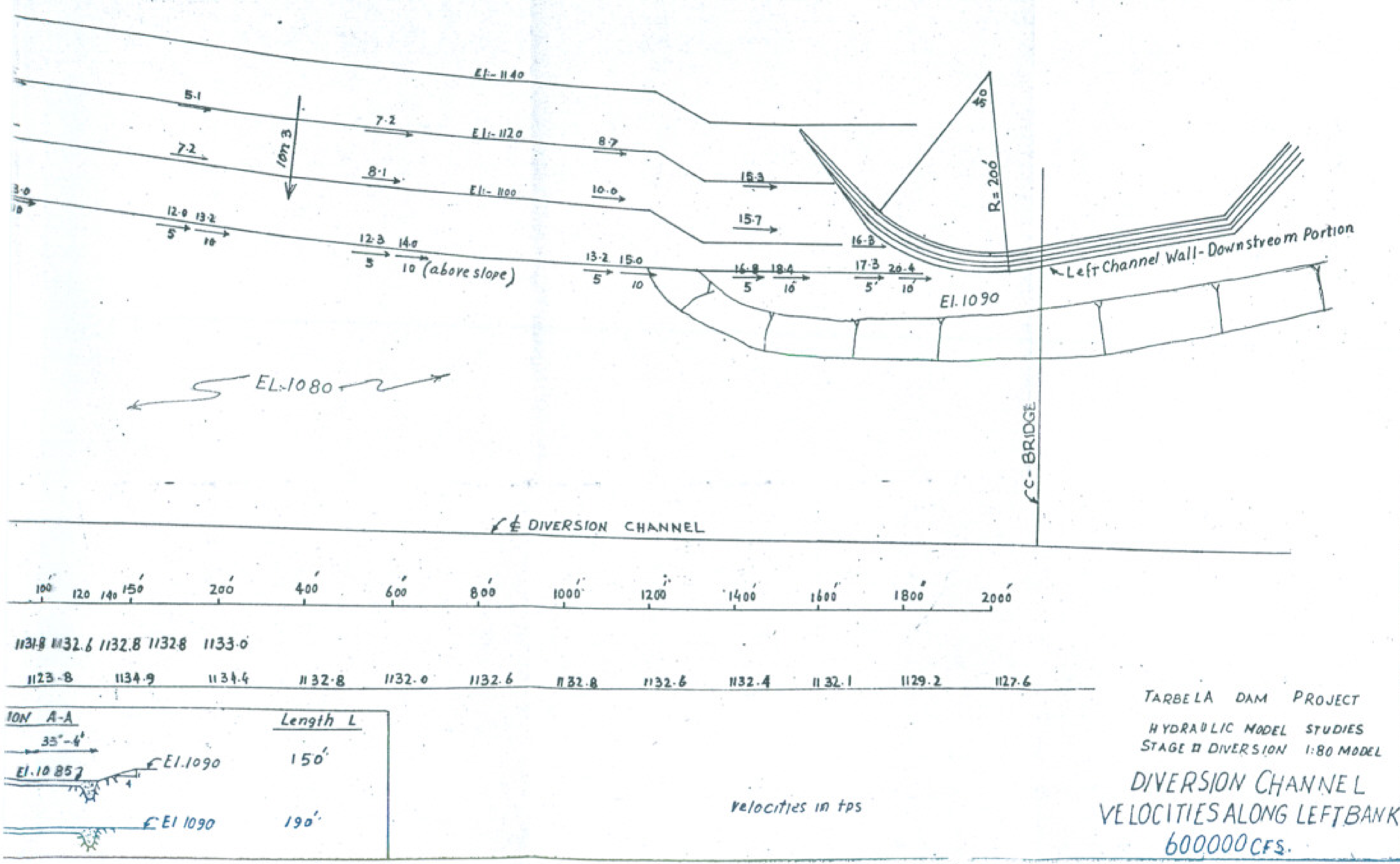
PLAN SHOWING ROCK LIMITS IN DIVERSION CHANNEL





L
Left Channel Wall Upstream Portion
Buttress Dam Apron
A
EL 1090
1 ON 20
EL. 1080
10 m 3
(above s
Toe of Jump
347'
DISTANCE IN FEET
(From end of buttresses)
0' 20' 40' 60' 80' 100' 120 140 150' 200' 400' 600' 80
WATER LEVELS
(F) 1121.0 1116.0 1119.8 1126.9 1130.8 1131.8 1132.6 1132.8 1132.8 1133.0
(P) 1120.6 1116.4 1111.8 1111.7 1117.1 1123.8 1134.9 1134.4 1132.8 1132.0
LEGEND
(F) Final Layout
(P) Preliminary Layout
SECTION A-A
66'-8"
33'-4"
El. 1090
El. 1085
El. 1090
Distance
℄ Road
El 1090
Length L
150'
190'

Fig-11.



TARBELA DAM PROJECT

HYDRAULIC MODEL STUDIES

STAGE II DIVERSION 1:80 MODEL

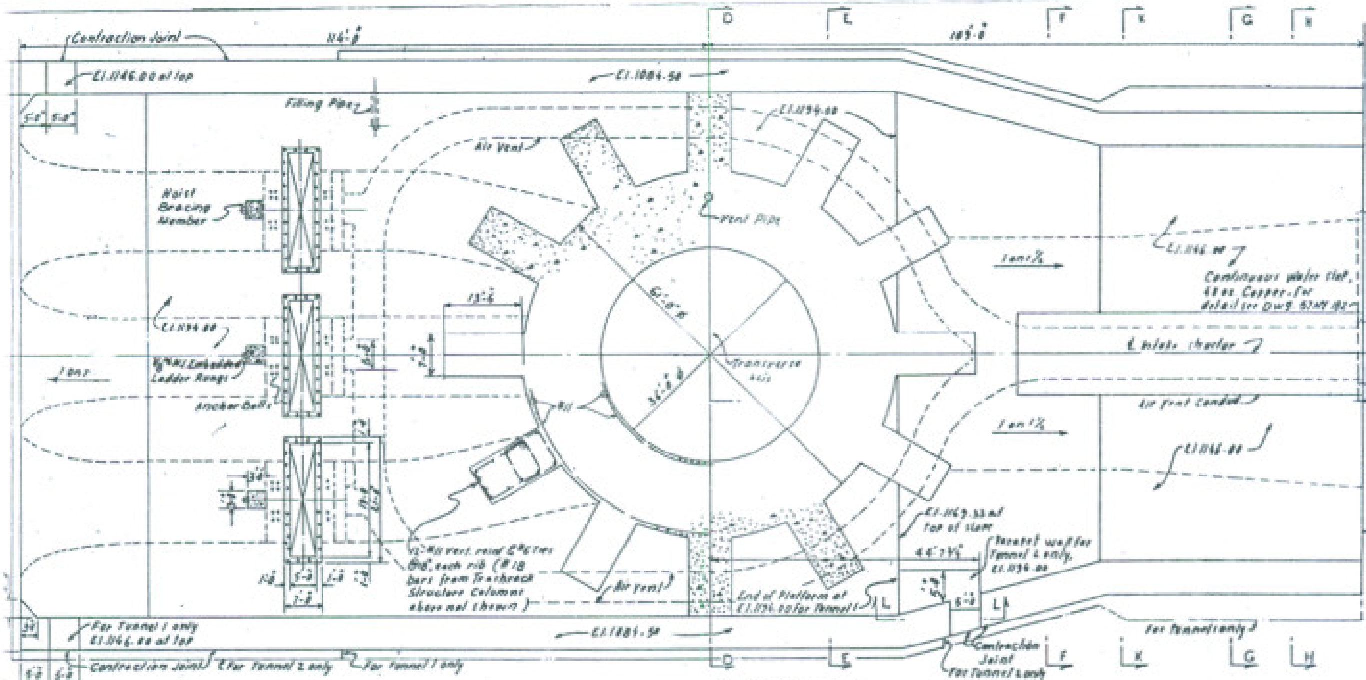
DIVERSION CHANNEL VELOCITIES ALONG LEFT BANK 600000 CFS.

FIG. 14

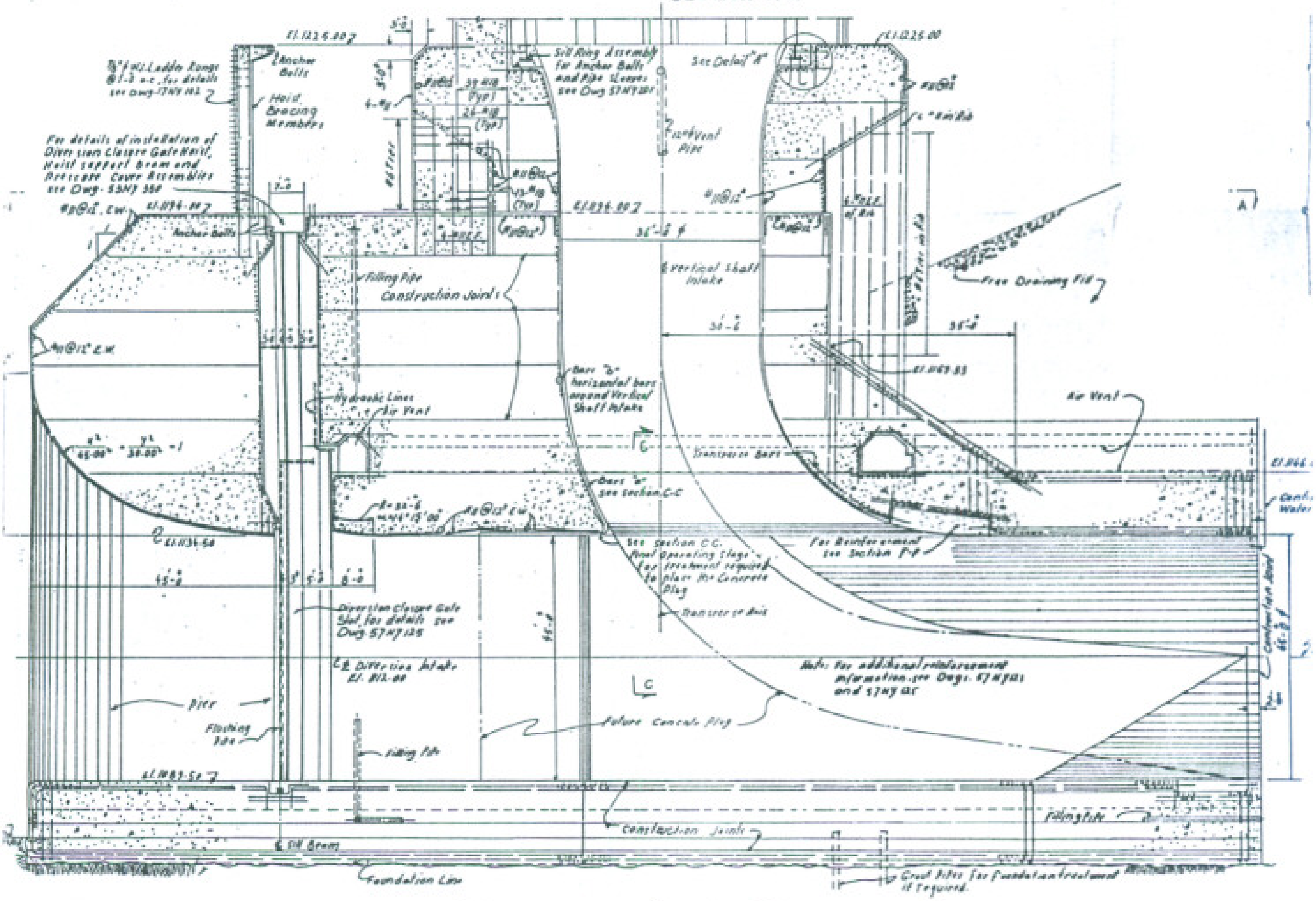
TARBELA DAM PROJECT

TUNNELS OUTLET AREA

JUU CUDIC



SECTION A-A



SECTION B-B

FIG.15(a)

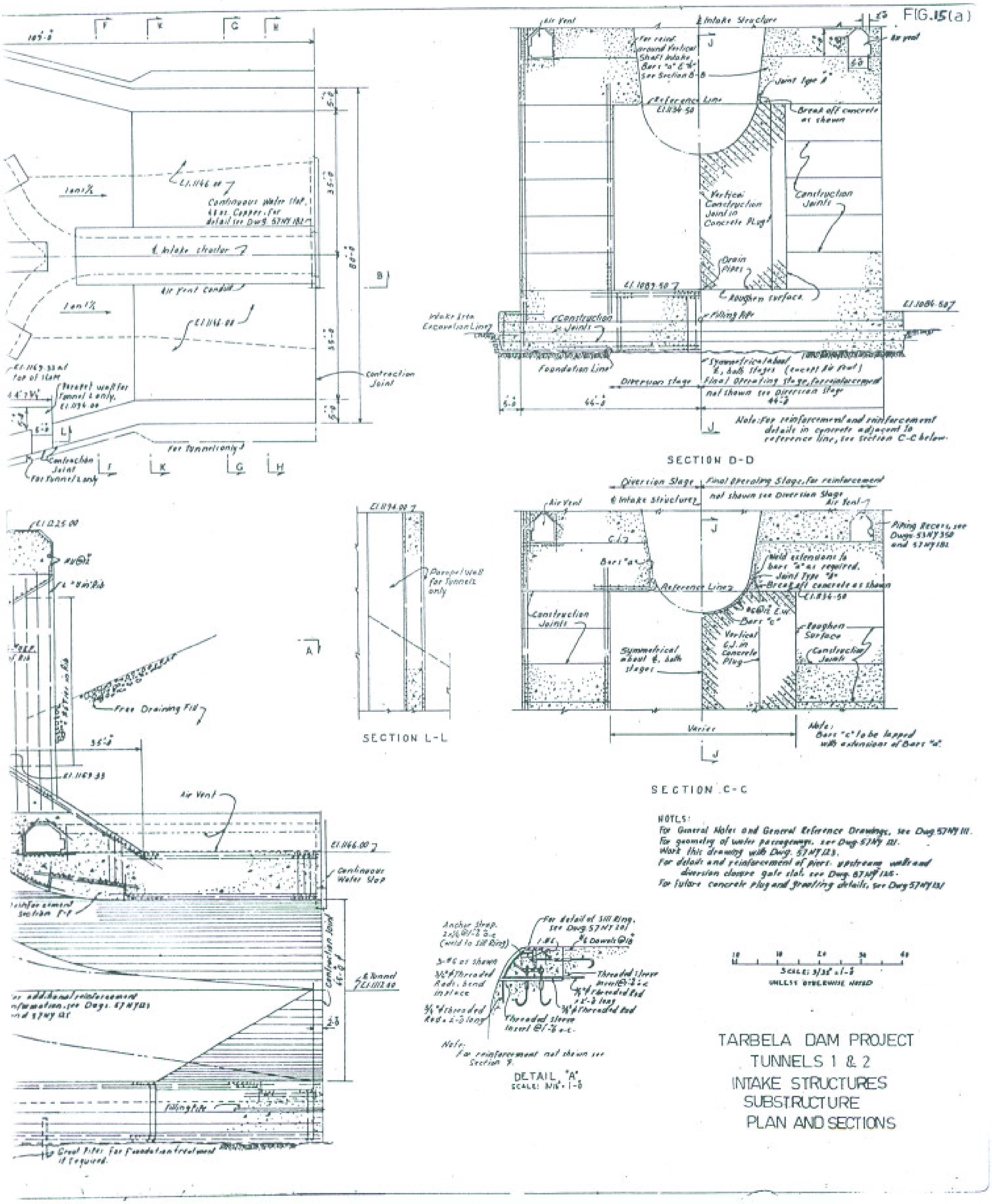
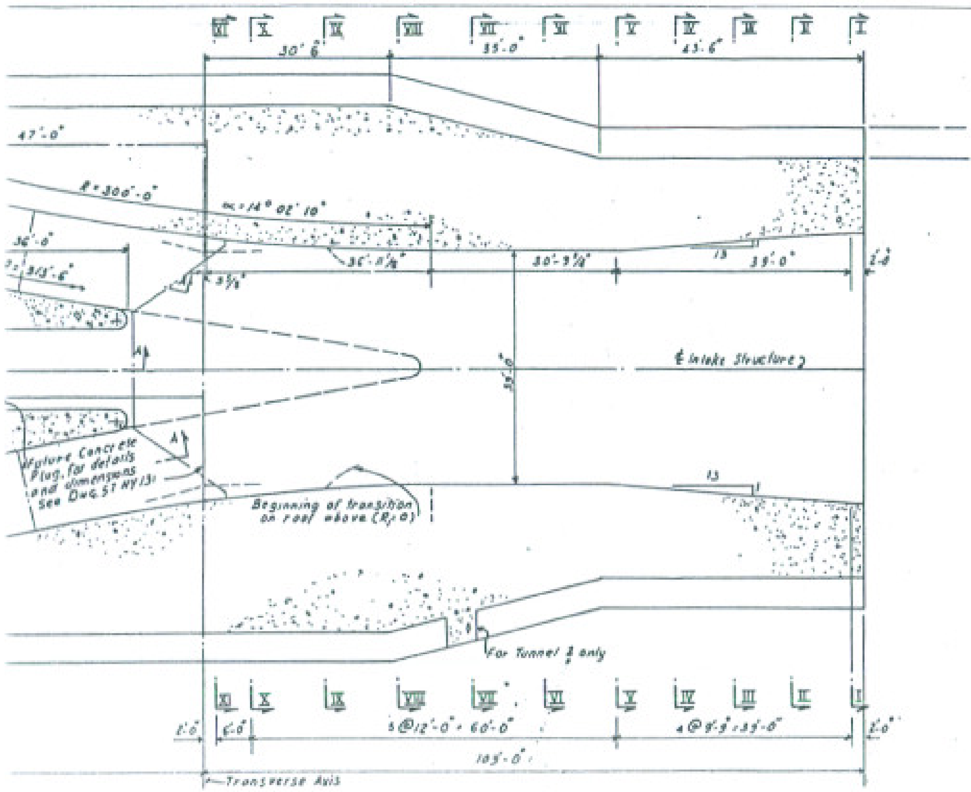
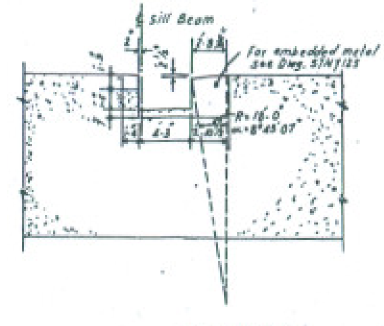

SECTION D-D
SECTION C-C
SECTION L-L
DETAIL "A"
Air Vent
Intake Structure
Reference Line
Construction Joints
Foundation Line
Diversion Stage
Final Operating Stage, for reinforcement not shown see Diversion Stage
Note: For reinforcement and reinforcement details in concrete adjacent to reference line, see Section C-C below.
Contraction Joint
Continuous Water Stop
Free Draining Fill
Parapet Wall for Tunnels only
Note: Bars "c" to be lapped with extensions of Bars "a".
NOTES:
For General Notes and General Reference Drawings, see Dwg. 57NY 111.
For geometry of water passageways, see Dwg. 57NY 121.
Work this drawing with Dwg. 57NY 123.
For details and reinforcement of piers, upstream walls and diversion closure gate slot, see Dwg. 57NY 126.
For future concrete plug and grouting details, see Dwg. 57NY 131
Note: For reinforcement not shown see Section 9.
SCALE: 3/32" = 1'-0"
UNLESS OTHERWISE NOTED
TARBELA DAM PROJECT
TUNNELS 1 & 2
INTAKE STRUCTURES
SUBSTRUCTURE
PLAN AND SECTIONS

FIG.15(b)



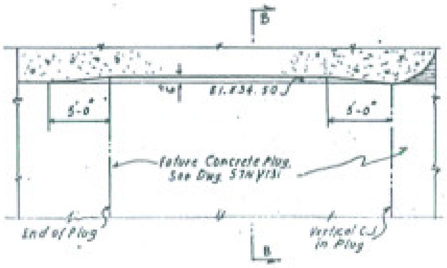
SECTIONAL PLAN AT THE EL. 1112.00

DIVERSION STAGE



DETAIL "A"

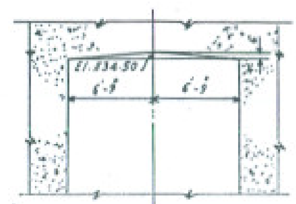
SCALE:- 1 IN. = 5 FT.



SECTION A-A

AT C.L. OF PASSAGEWAY

SCALE:- 1 IN. = 5 FT.

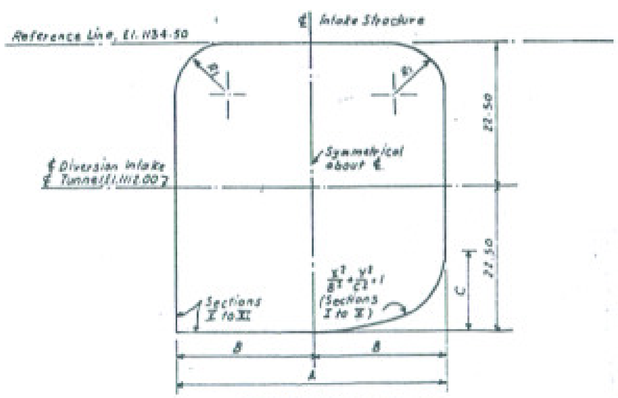


SECTION B-B

SCALE:- 1 IN. = 5 FT.

NOTE.

For General Notes and General Reference Drawings, see Dwg. 57 NY 111
For blockout and recess Concrete, and for embedded metal in slot of diversion closure gate, see Dwg. 57 NY 125.
For Concrete plug in diversion intake, see Dwg. 57 NY 131.



SECTIONS I TO XI

DIVERSION STAGE

SCALE:- 1 IN. = 5 FT.

TABLE OF COORDINATES			
Point	D	X	Y
p_1	45.00	0	45.00
p_2	36.85	53.00	45.00
p_3		55.34	45.10
p_4	36.00	58.47	45.42
b_1	-	0	0
b_2	-	55.00	8.15
b_3	-	58.51	9.00
b_4	-	63.95	9.86
M	-	59.00	81.00
N	-	101.00	135.50

Section	A	B	C	R_1
I	45.00	22.50	22.50	22.50
II	43.50	21.75	16.875	21.75
III	42.00	21.00	11.25	21.00
IV	40.50	20.25	5.625	20.25
V	39.00	19.50	0	19.50
VI	39.00	19.50	-	*Varies
VII	39.00	19.50	-	*Varies
VIII	39.09	19.545	-	*Varies
IX	39.99	19.995	-	0
X	41.86	20.93	-	0
XI	43.15	21.58	-	0

* Wall Surfaces to form a smooth curve of varying radius connecting the vertical Surface of the Diversion intake below to the curved surface of the Vertical Shaft Intake coming down from above, and to be tangent to these surfaces at the points of connection.

TARBELA DAM PROJECT

TUNNELS 1 & 2

INTAKE STRUCTURES

SUBSTRUCTURE

SECTIONAL PLAN & GEOMETRY

SCALE: 3/32" = 1'-0" UNLESS OTHERWISE NOTED

57 NY 121

AKE

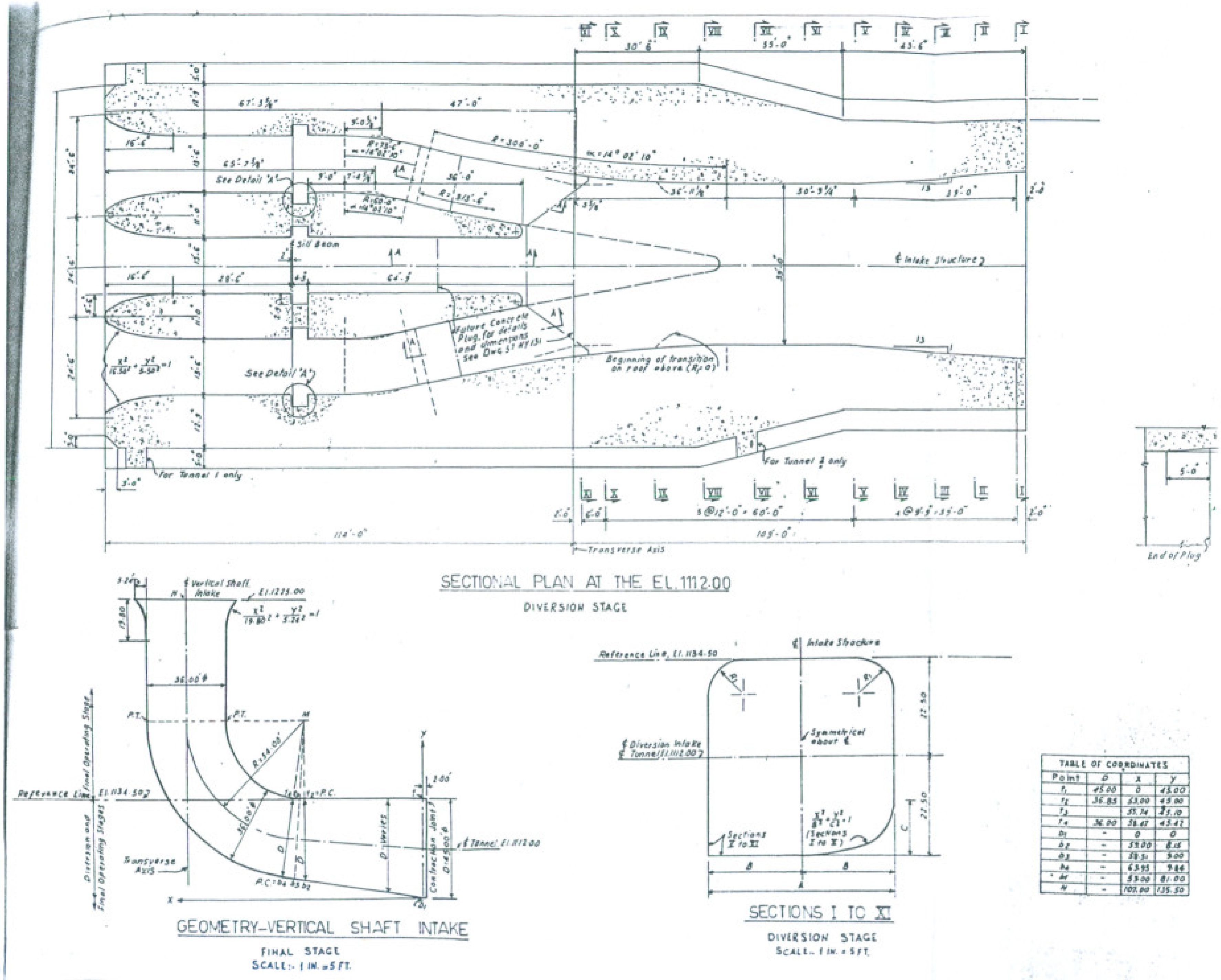
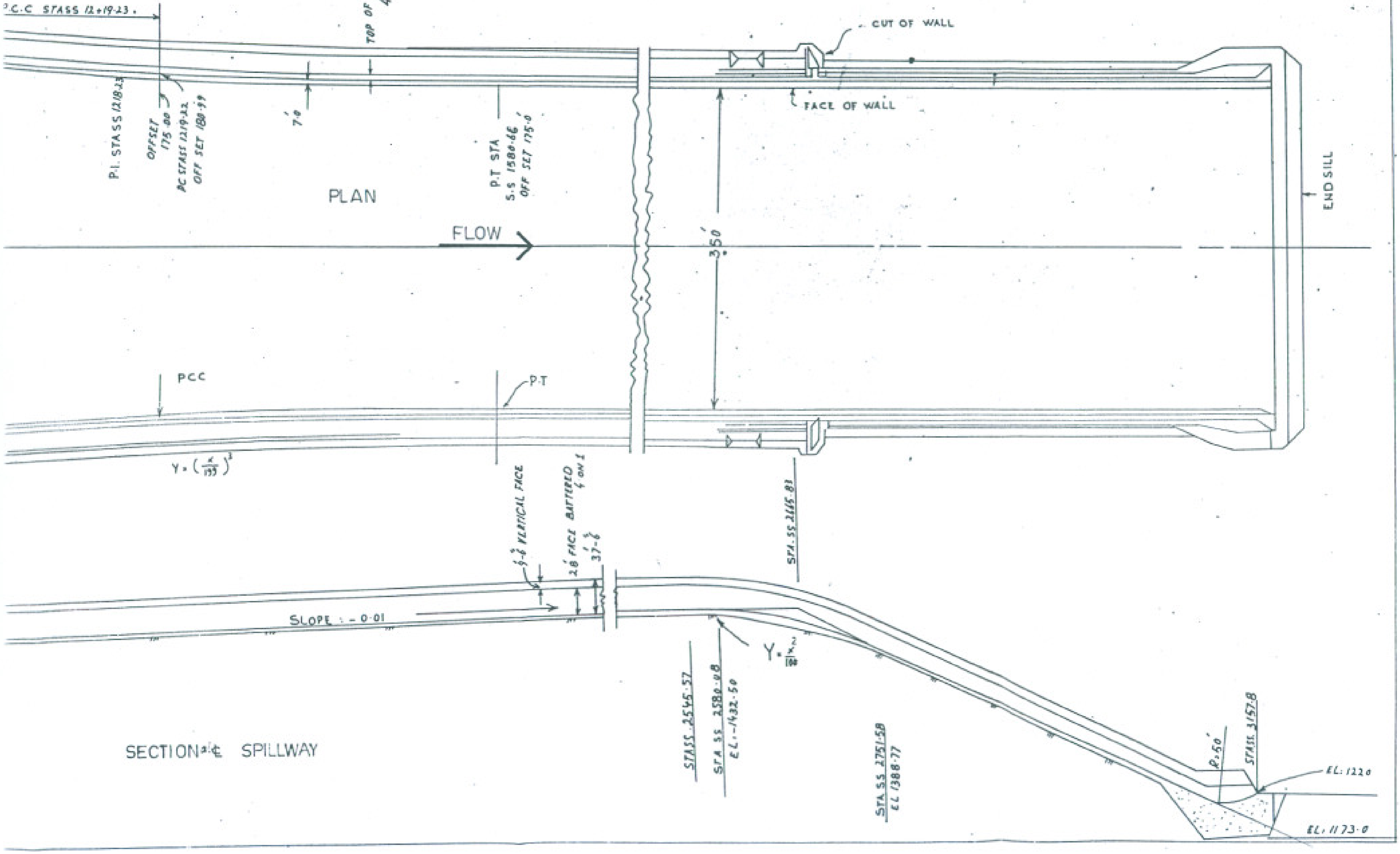


TABLE OF COORDINATES			
Point	D	X	Y
r_1	45.00	0	45.00
r_2	36.85	53.00	45.00
r_3		55.74	45.10
r_4	36.00	58.47	45.42
b_1	-	0	0
b_2	-	53.00	8.15
b_3	-	58.51	9.00
b_4	-	63.95	9.84
M	-	53.00	81.00
N	-	109.00	135.50

FIG. 31(a)

TARBELA DAM PROJECT
SERVICE SPILLWAY
SCALE: 1" = 100'



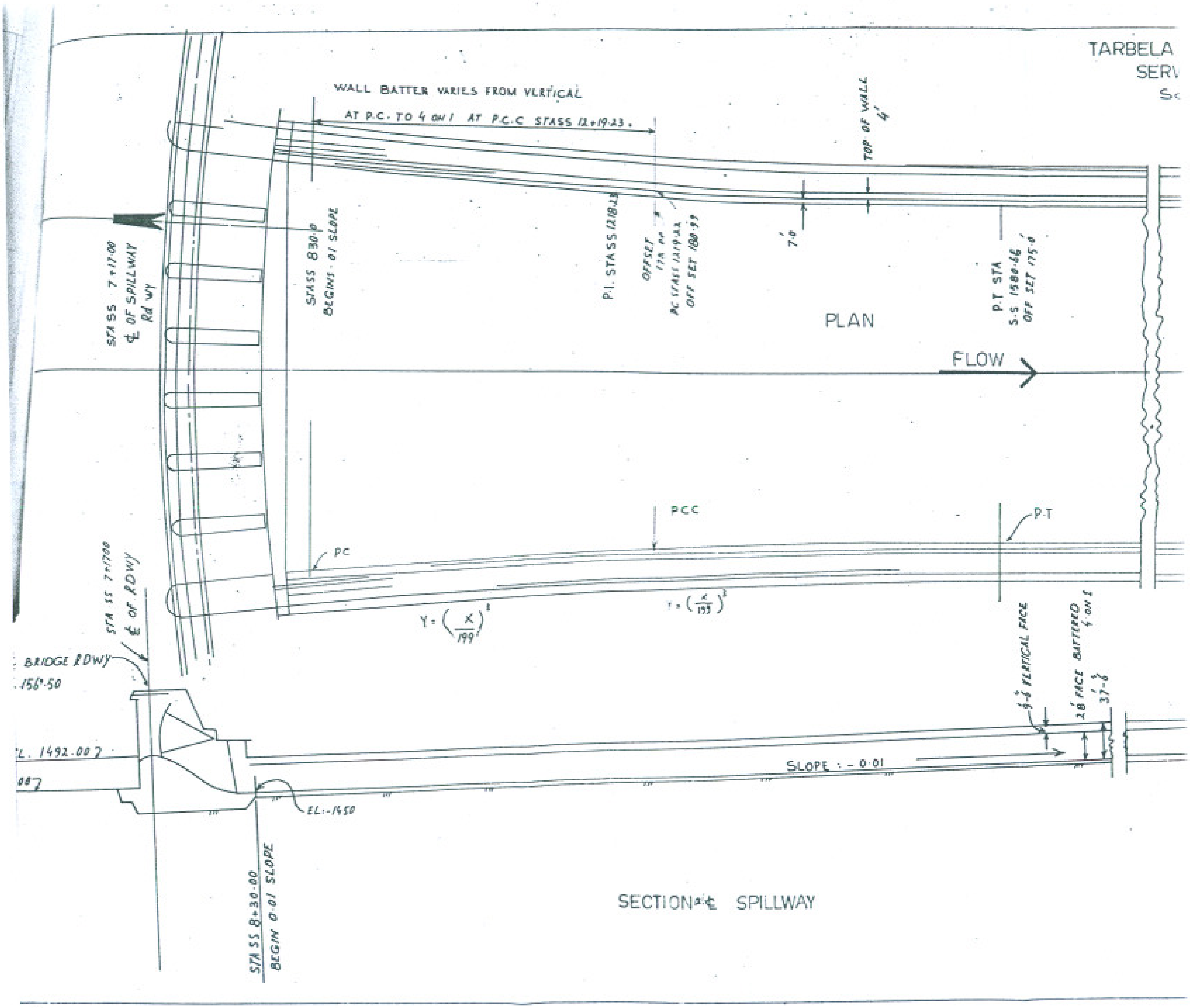
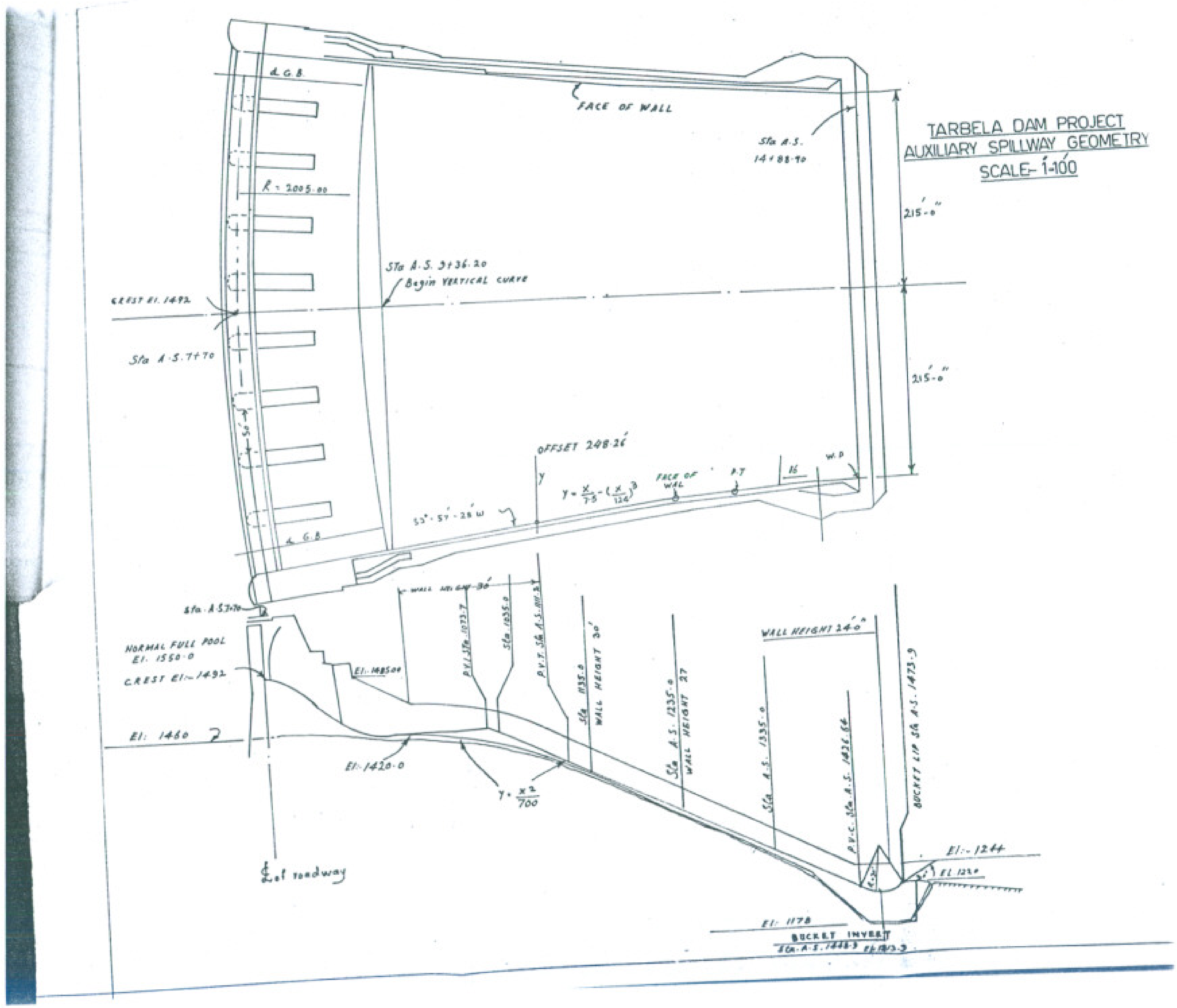

TARBELA
SERV
WALL BATTER VARIES FROM VERTICAL
AT P.C. TO 4 ON 1 AT P.C.C STASS 12+19.23.
TOP OF WALL 4'
7'0
STASS 830.0
BEGINS .01 SLOPE
P.I. STASS 1218.23
OFFSET
PC STASS 1219.23
OFF SET 180.99
P.T STA
S.S 1580.66
OFF SET 175.0
PLAN
FLOW
STASS 7+17.00
℄ OF SPILLWAY
Rd wy
PCC
P.T
PC
$Y = \left(\frac{X}{199}\right)^2$
$Y = \left(\frac{X}{199}\right)^2$
STA SS 7+17.00
℄ OF RDWY
BRIDGE RDWY
EL. 1492.00
EL:-1450
SLOPE : - 0.01
9'-6" VERTICAL FACE
28' FACE BATTERED 4 ON 1
37'-6"
STA SS 8+30.00
BEGIN 0.01 SLOPE
SECTION ℄ SPILLWAY

FIG.31(b)



TARBELA DAM PROJECT
AUXILIARY SPILLWAY GEOMETRY
SCALE- 1-100