A STUDY OF THE EROSION AT THE TOE OF A DAM AND AN INVESTIGATION OF STILLING DAMS

THESIS FOR THE DEGREE OF M. S.

R. O. Abel

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A Study of the Erosion at the Toe of a Dam
and
An Investigation of Stilling Dams

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Master of Science

THESIS

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-Appreciation-

I wish to acknowledge my indebtedness to Professor C. M. Cade for his helpful suggestions in the preparation of this thesis.

Introduction

The fact that there appear now and then articles on dams where trouble with erosion is experienced shows that there is still room for investigation along this line. In recent years engineers have turned to the use of models for the solution of the problem of erosion. However, most of the models were made for the solution of the problems pertaining to some particular dam rather than for dams in general. Models made for this purpose have borne out the fact that the laws of hydraulic similitude hold true. The Conowingo Dam on the Susquehanna River in Maryland is an example of this. An exact model was made of the dam before construction and the erosion was studied below the toe. An examination of the riverbed below the dam after three years of service showed the results to be as predicted from the model tests.

It is the purpose of this thesis by the aid of a specially constructed model to make a study of the erosion at the toe of a dam and to evolve a design that may be applicable to any dam if properly applied. Every effort was made to make the conditions comparable to those in practice. The apron was made so that all types of energy absorbers could be fastened to the apron and adjusted to very small distances. The dam was supported ten inches above the floor of the flume by legs fastened to the back end. Sand was placed in the flume to the depth desired for the particular test. The tail-water could also be regulated

to the desired depth. Glass observation windows were placed along the sides.

Many types of energy absorbers were tested, many that do not appear in this thesis. Only those that were most successful were incorporated in the results. After having found the best type of energy absorber, a law was worked out for its design. This law will be found in the conclusion.

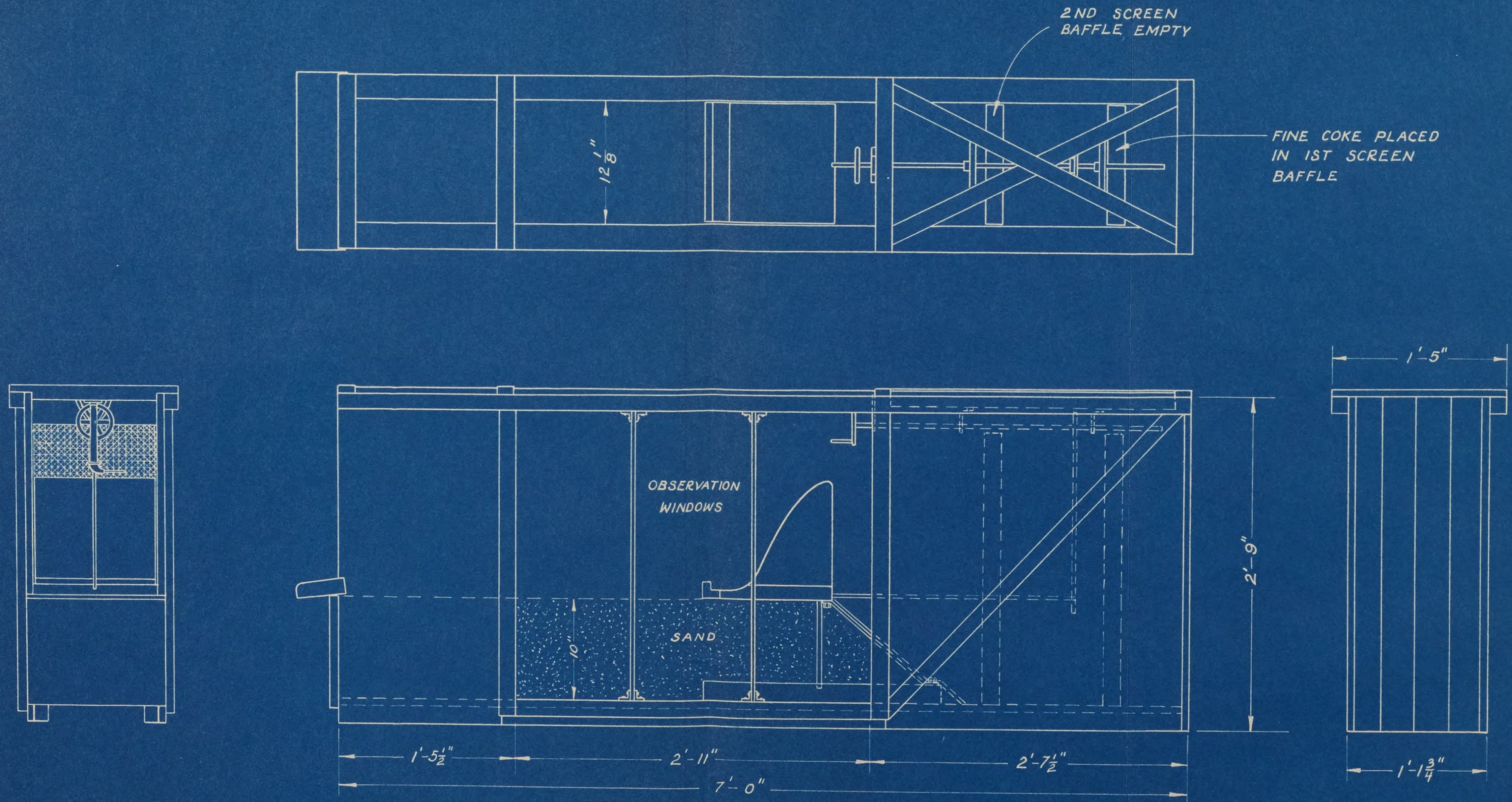
Construction of Model

In order to have a model with the desired flexibility and yet producing the same effects found in actual practice, a great deal of time was spent in its design and construction.

One of the interesting things about the model is the coke baffle, for due only to this was it possible to make the model as short as it is. The model is seven feet long, one foot wide inside, and two feet six inches high. The distance from the end at which the water is admitted, to the dam, is only two feet nine inches. This made it imperative that the water be completely stilled in a very short distance. Coke baffles having been used successfully in other recent models, it was decided to try them in this model. Two screens were made having two faces placed an inch and a half apart. The screens were placed across the flume leading to the dam in the positions shown in the plates and drawings. The first one was filled with fine coke, the second one was left empty with the idea of filling it if necessary.

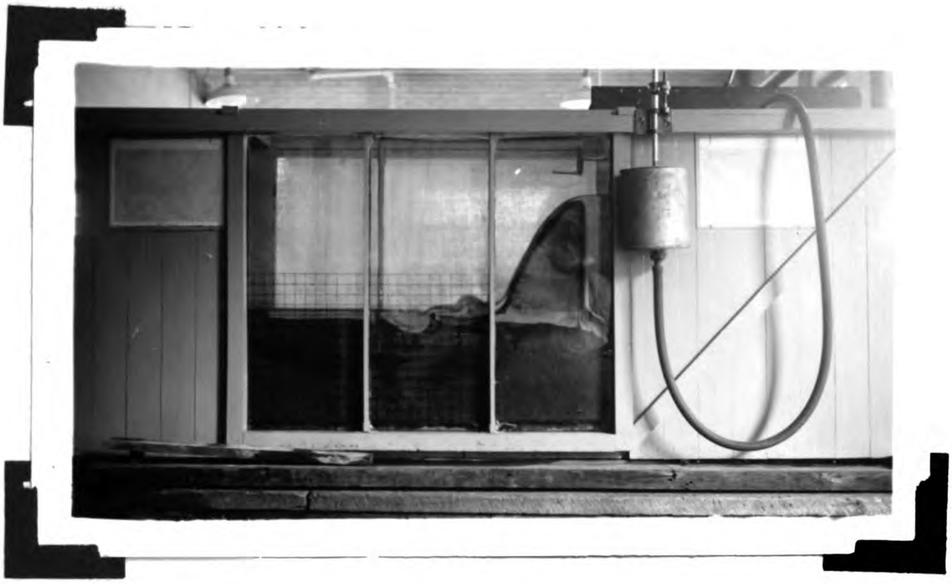
The results were all that could be desired. The water was almost completely stilled by the first baffle. After leaving the second empty baffle, the water approached the dam so smoothly that it looked like a sheet of glass. More perfect results could not be obtained.

The model was made of wood and lined on the inside with twenty-four gauge galvanized sheet iron. A board ten inches



PLAN OF MODEL

SCALE 1" = 1'-0"

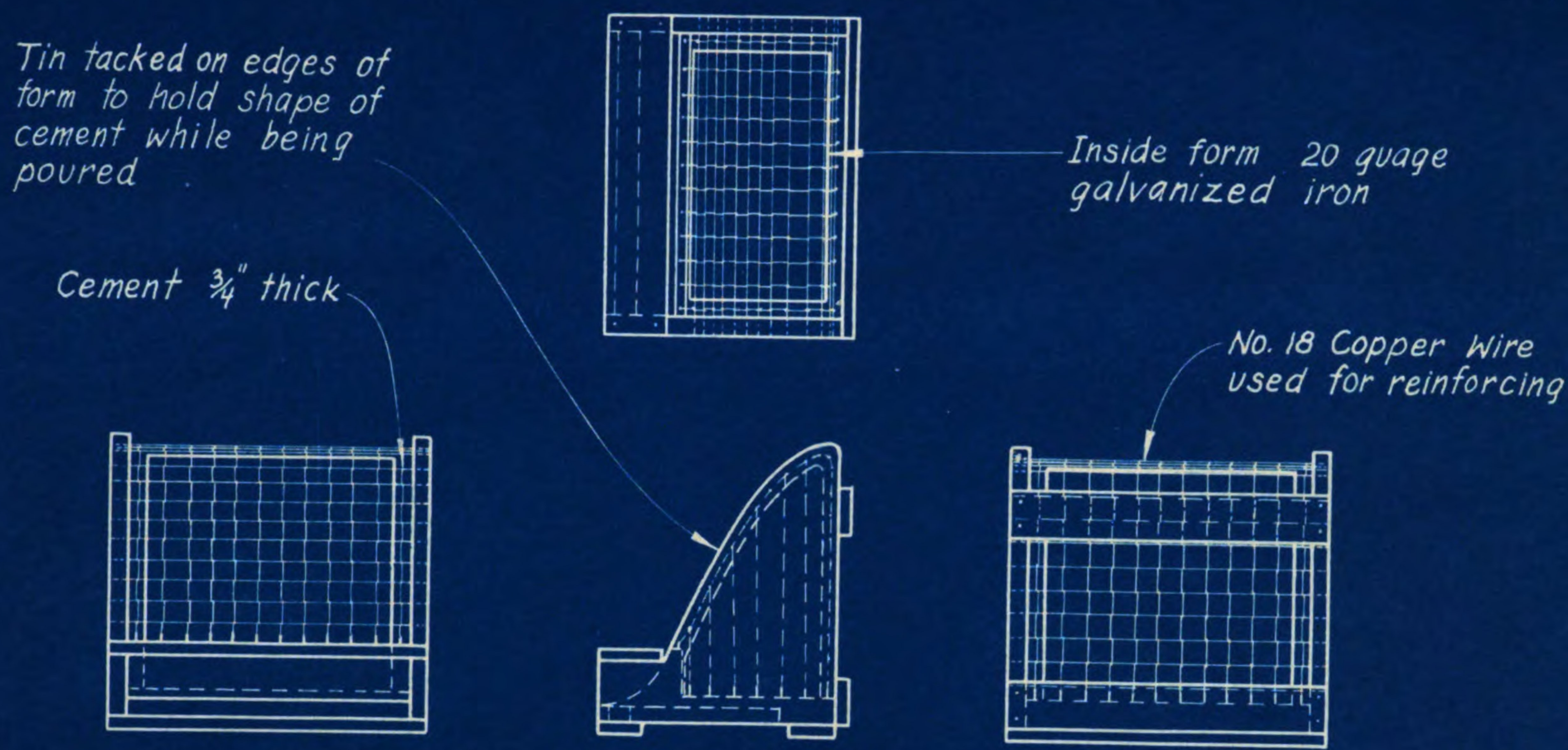


Side view of model

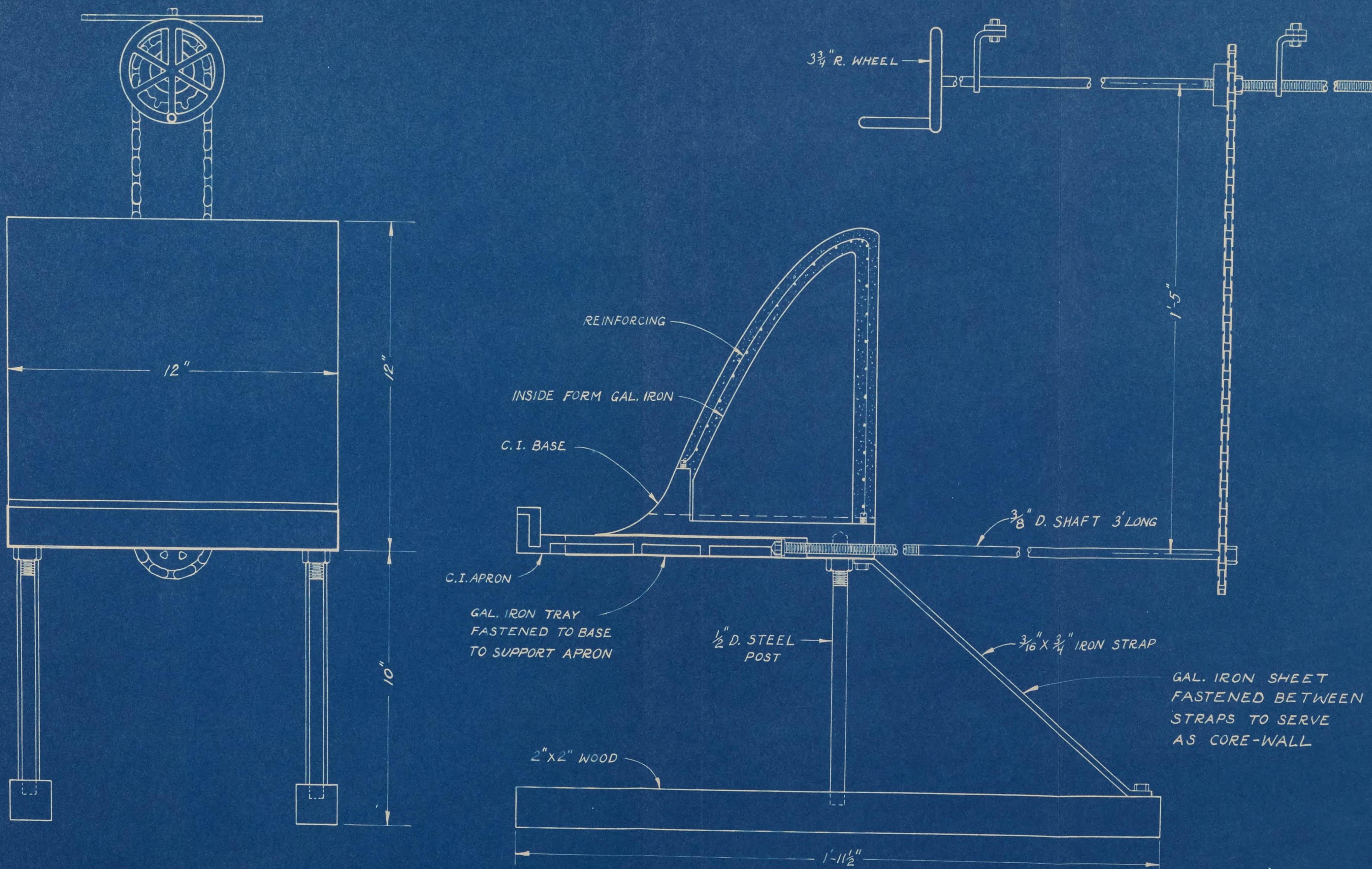
End view of model showing weir adjustment

high was placed across the end at which the water ran out in order to hold the sand in the bottom at that depth. The sand filled the bottom from the end back to the core-wall under the dam. Back of the core-wall the water filled the flume down to the bottom. Observation windows three feet long and extending from the top to the bottom, were placed on each side one foot and four inches from the down stream end of the flume. These provided a view of the dam and the sand below it.

The dam itself is made of reinforced concrete, hollow on the inside, with a cast iron base. It was necessary to make the base of cast iron to keep the edge of the toe from chipping off. The apron is also made of cast iron, finished off on the upper surface. In the following pages is a plate showing the method of placing the reinforcing in the dam. Two wooden forms were cut to the exact shape of the dam and fastened one foot apart, inside dimension. These were in turn fastened to the cast iron form of the base. Studs with a hole in each were put one inch apart all around the edge of the base. Small holes were also drilled three quarters of an inch apart and three eights of an inch from the edge around the sides of the form. Number eighteen copper wire was laced back and forth through these holes to form the reinforcing. Before the reinforcing was started, a galvanized sheet iron form was placed on the inside. This form was three quarters of an inch smaller all around than the outside of the form, making the cement



DETAILS OF REINFORCING
IN FORM



END VIEW AND SECTION THRU DAM

SCALE 3" = 1'-0"

Side view showing the water going over the dam. The hook guage and tank are at the right.

View over top of dam showing the hand wheel and the second screen baffle. Notice the stillness of the water going over the dam.

three-quarters of an inch thick. Tin was tacked on the edges of the form to hold the cement while it was being poured. As the tin was carried up the cement was rammed in between the tin and the inside form. When the cement had been poured up to the top, the mould was tipped over forward till the back was level, the cement was then poured on the back and finished off. It was allowed to set in this position.

As shown in the drawing of the end view and section through the dam, a hole was drilled and tapped through the center of the base. A three-eights inch threaded shaft was run through the hole and fastened on to the back end of the apron by means of a collar so that it could be turned around. On the other end of the shaft was fastened a sprocket. Another three-eights shaft with a hand wheel on one end was hung from the braces in the back of the flume. A sprocket of the same size was fastened on this shaft over the other sprocket and the two were connected by a chain. By means of this arrangement the apron could be moved out and in by turning the hand wheel.

In order to keep the apron from falling down, a tray was fastened to the base to hold it. The apron slid back and forth on this tray which was made of galvanized sheet iron.

In connection with the arrangement for holding the dam up, an interesting thing occurred. One half inch steel posts were fastened to the bottom of the dam and set in two by twos to hold the dam up ten inches from the bottom. Braces were run

from the back of the dam to the end of the two by twos as shown in the drawing. No provision was made to keep the water from running under the dam, thinking it would be sufficient to pack sand bags and sand in back of it. However, when the dam was first tried out, it was next to impossible to keep the water from going under the dam, and once it started going it took all the sand with it. I believe that I have never seen anything as persistent as that water. The dam was then taken out and a galvanized sheet iron core-wall was made to fit across the flume in back of the dam. The dam was replaced and it was found that even the core-wall had to be sealed around the edges with a fillet of putty and painted in order to keep the water from running under the dam. Even a hole the size of a pin would let enough water through to erode a small channel in the sand. It was finally made water tight in back of the dam.

At the end of the apron there is a slot in to which the stilling dam fits. The stilling dam is also made of cast iron. The stilling dam may be removed and any shape of stilling device may be inserted in the slot. Most of the different types were made from galvanized sheet iron and were bent in to the desired shape on bending machines. On each device a ridge was either fastened or bent in to fit in the slot. This was to hold it ridgely in place.

A weir made of galvanized iron was made to fit in the outlet end of the flume. The end of a three-sixteenths inch shaft was fastened to the center of the weir, the other end of the shaft was threaded. By means of a handle on another hollow shaft, fastened at one end by a collar, and threaded on the inside in the other end, the weir was raised and lowered by screwing the larger shaft over the smaller one. This made it possible to keep the tail-water at any desired level.

The depth of water over the dam was measured by means of a hook gauge lowered in to a can fastened on the side of the flume. Water was siphoned in to the can by means of a hose. One end of the hose was fastened to the bottom of the can and the other was placed below the surface of the water in the flume between the two baffles. For rapid variations of head the siphon could not be used due to siphon loss. When conditions were constant the method gave very accurate results. It was necessary to measure the depth only when conditions were constant.

During the first tests on the model, the water was measured by means of a weighing bin on a set of scales. A record was kept of the hook gauge readings and a hook gauge curve was made from these. In the later tests the hook gauge curve was used to find the quantity of water flowing.

Another curve was made for the depth of tail-water required to form the hydraulic jump. It was not necessary to use this curve during the tests with the plain apron, since it was possible to cause the hydraulic jump to form at any point on the apron by means of the adjustable weir at the end of the flume. The curve was used with the stilling dam and

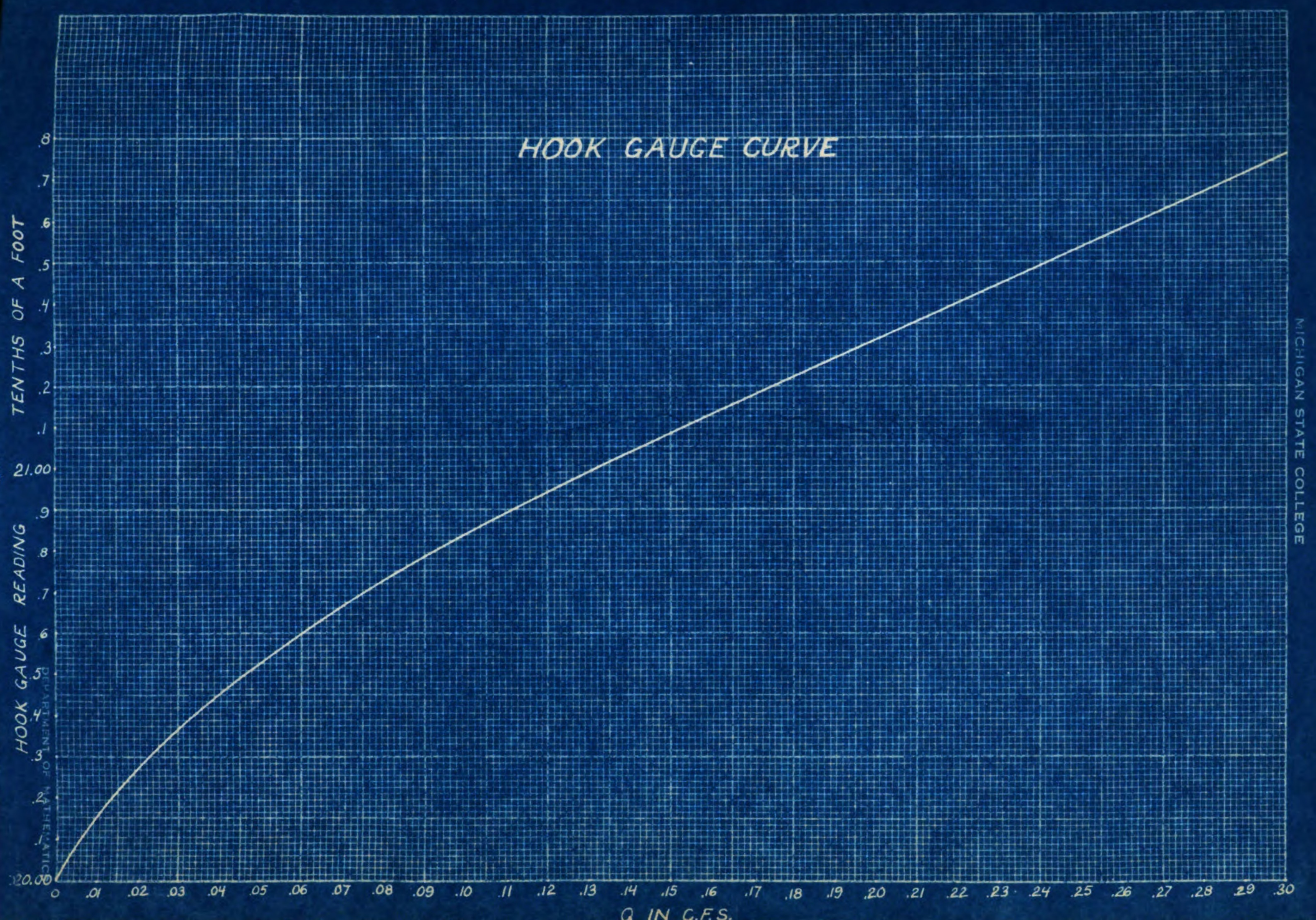
other energy absorbers as an aid in determining the depth to be expected of the tail-water. This was the only means of obtaining the right depth except by building a very long flume.

The formula used in constructing the hydraulic jump curve was

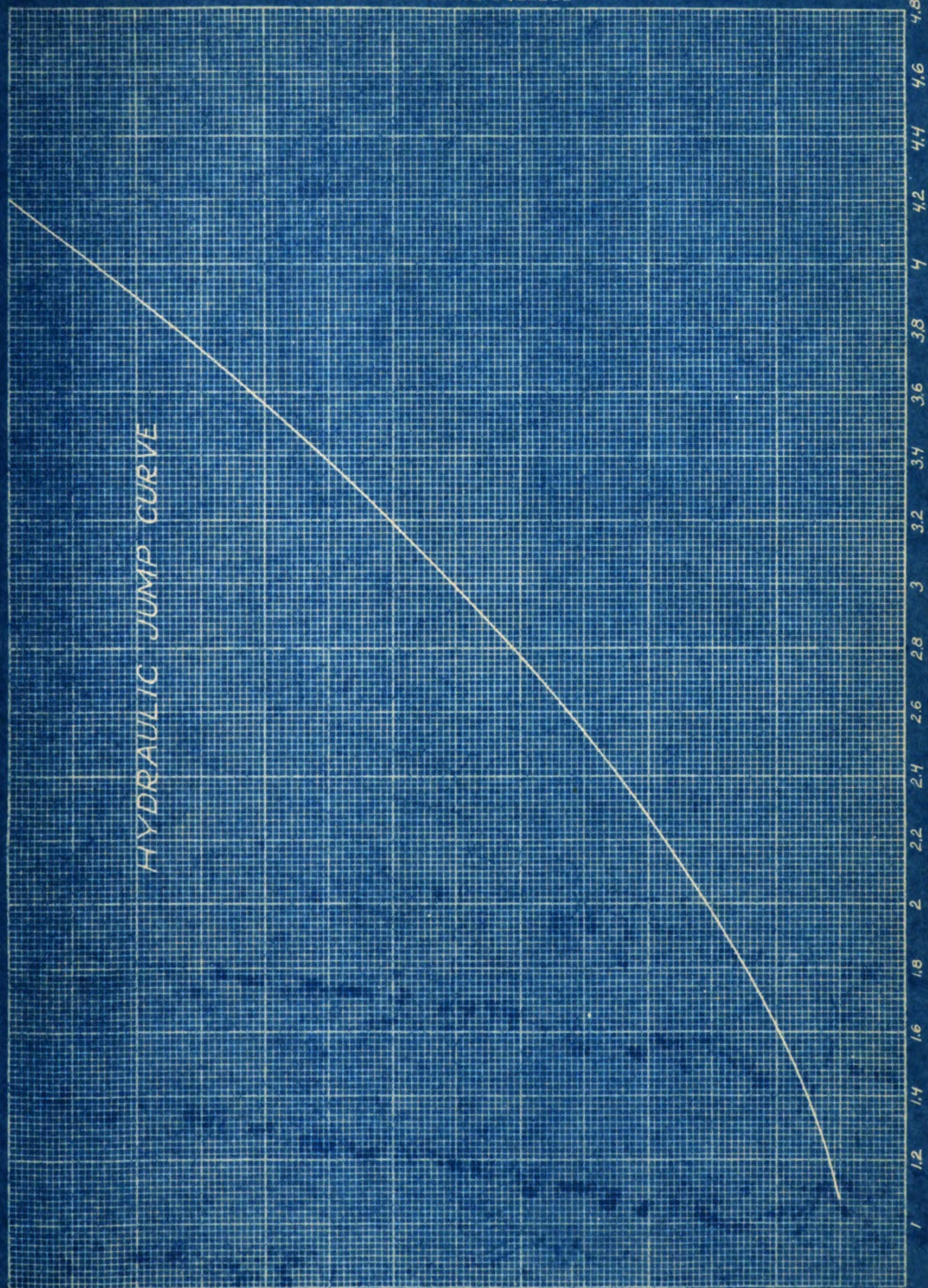
$$d_j = -\frac{d_1}{2} \pm \sqrt{\frac{2V_1^2 d_1}{g} + \frac{d_1^2}{4}}$$

d_1 = The theoretical depth at the toe of the dam

V_1 = The theoretical velocity at the toe of the dam


HOOK GAUGE CURVE
HOOK GAUGE READING
TENTHS OF A FOOT
Q IN C.F.S.
20.00
21.00
MICHIGAN STATE COLLEGE
DEPARTMENT OF MATHEMATICS

MICHIGAN STATE COLLEGE

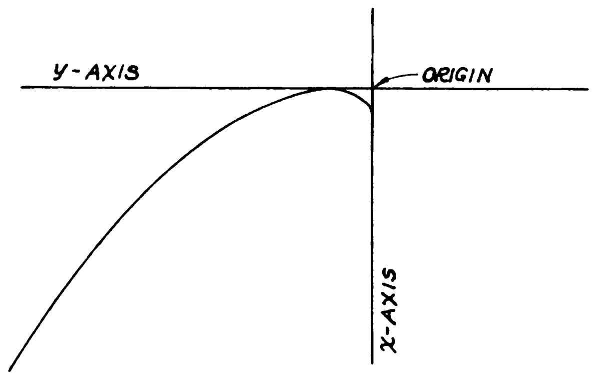


DEPARTMENT OF MATHEMATICS

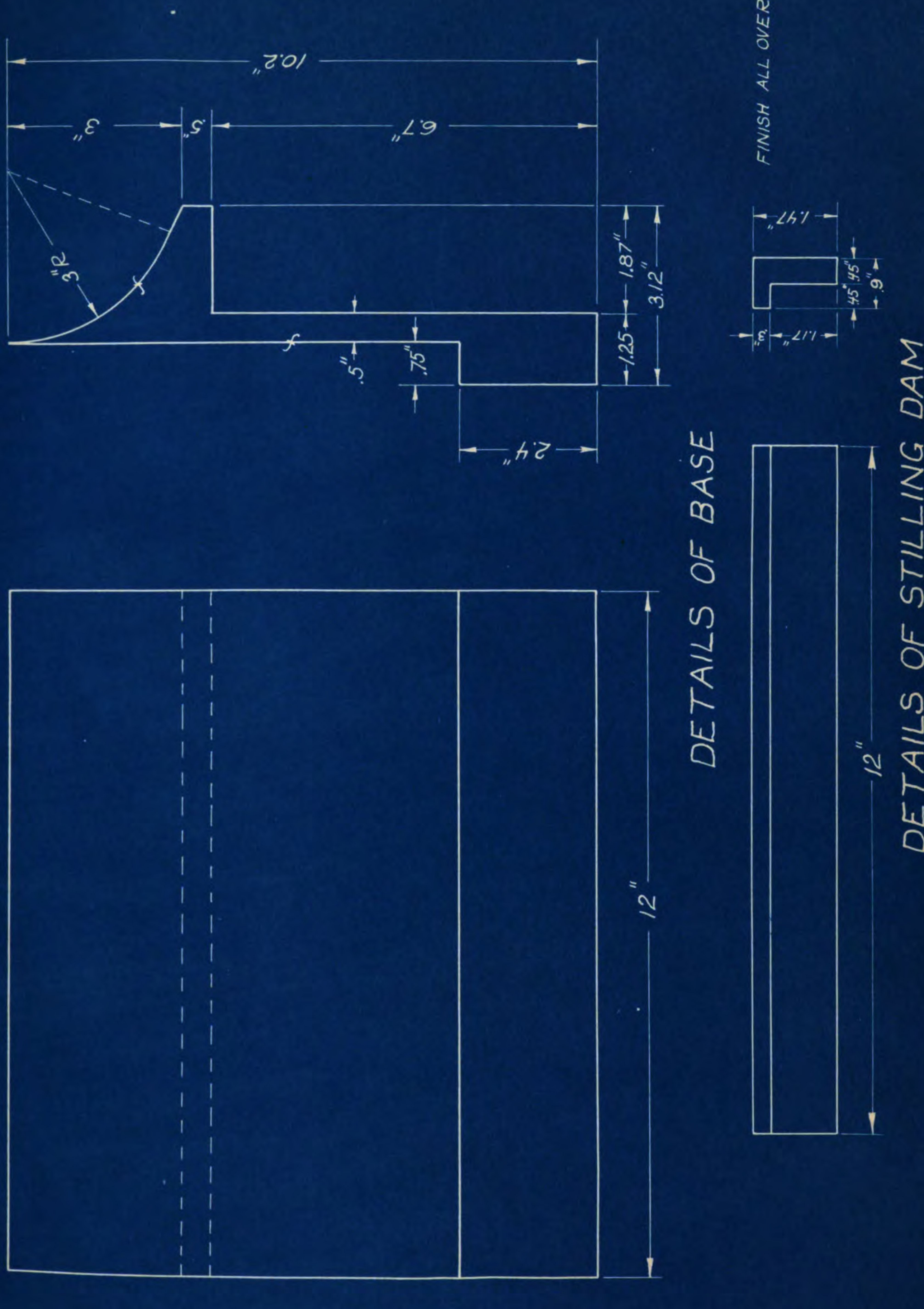
Shape of Crest

The model was designed on the basis of a dam twenty feet high with a head of three feet on the crest. The ratio was taken twenty to one, making the model dam one foot high and the head on the crest 1.8 inches.

Following is a table of the coordinates of the downstream face, the upstream face being vertical. The x axis coincides with the upstream face of the dam. The y axis is tangent with the crest at its highest point.



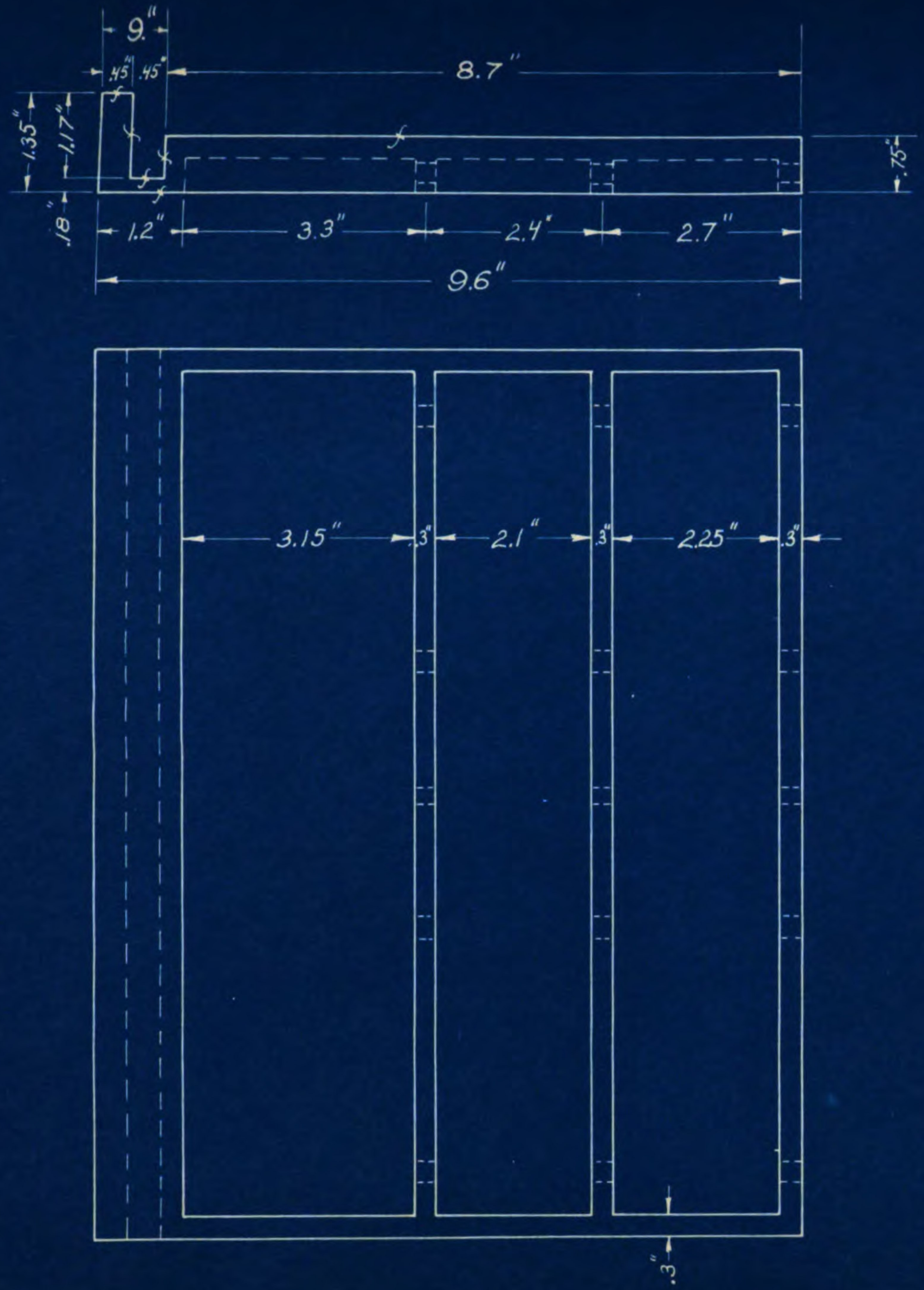
y	x Masonry Line	Theoretical Water Sheet Upper Nappe	Theoretical Water Sheet Lower Nappe
0.00	.2268	-1.498	.227
.18	.0648	-1.445	.065
.36	.0126	-1.390	.013
.54	.0000	-1.331	0
.72	.0648	-1.263	.013
1.08	.108	-1.118	.113
1.44	.256	- .920	.276
1.80	.462	- .684	.481
2.16	.715	- .394	.738
2.52	1.018	- .054	1.061
3.06	1.565	.549	1.655
3.60	2.195	1.247	2.360
4.50	3.530	2.70	3.780
5.40	5.075	4.50	5.600
6.30	6.875	6.59	7.675
7.20	8.875	9.00	10.100
8.10	11.200	11.78	12.880

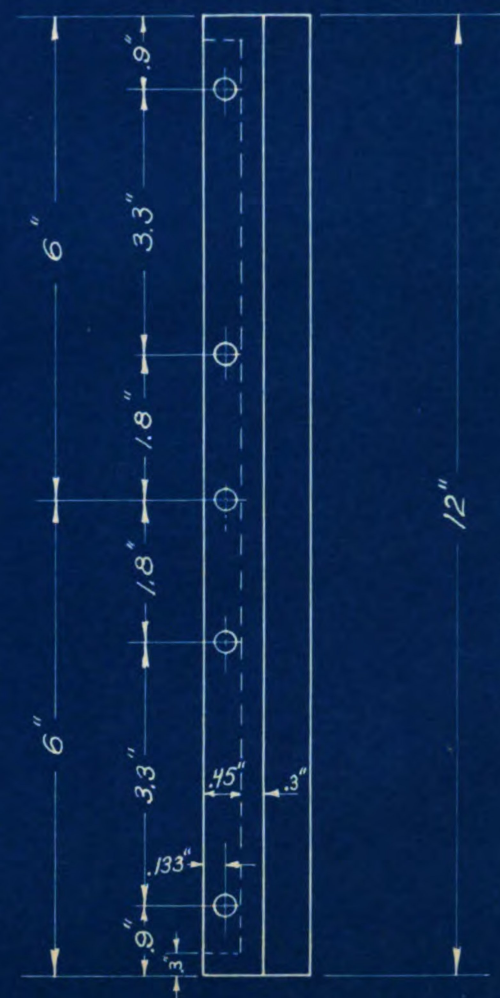


DETAILS OF BASE
DETAILS OF STILLING DAM
FINISH ALL OVER
10.2"
3"
.5"
6.7"
3"R
1.87"
3.12"
1.25
.5"
.75"
2.4"
12"
1.47"
.45"
.45"
.9"
.3"
1.17"
12"

DETAILS OF APRON

SCALE FOR MODEL $1'' = 0'-2\frac{2}{3}''$
SCALE FOR 20' DAM $1'' = 4'-0''$





Effect of Plain Apron on Erosion

With the apron as shown in plate number one, the water was allowed to run for seventeen hours. This was done in an effort to secure an action observed in dams where the erosion went completely under the apron. When the dam was left at three o'clock in the afternoon, there was .048 cu. ft. per second of water flowing over the dam. During the night the flow varied so that in the morning at eight o'clock there was .058 cu. ft. per second flowing. Also, when the dam was left at eight o'clock the tail-water level was adjusted so that the water at the edge of the apron was on the verge of flowing back over the swiftly moving water at the bottom of the dam.

Before leaving the dam, it was observed that erosion had started to occur as shown on plate one by the dotted line. In the morning the erosion was as shown by the solid line. Due to the fact that the head of water had increased, the erosion had moved down stream. After making considerable tests with a fair head of water flowing, it was found that the erosion was of the same shape and location, always a dip occurring some distance down stream from the dam. As the head increased the hole formed became deeper and also moved farther down stream away from the dam.

Another thing observed was, that as the head increased and the erosion moved down stream becoming deeper and deeper

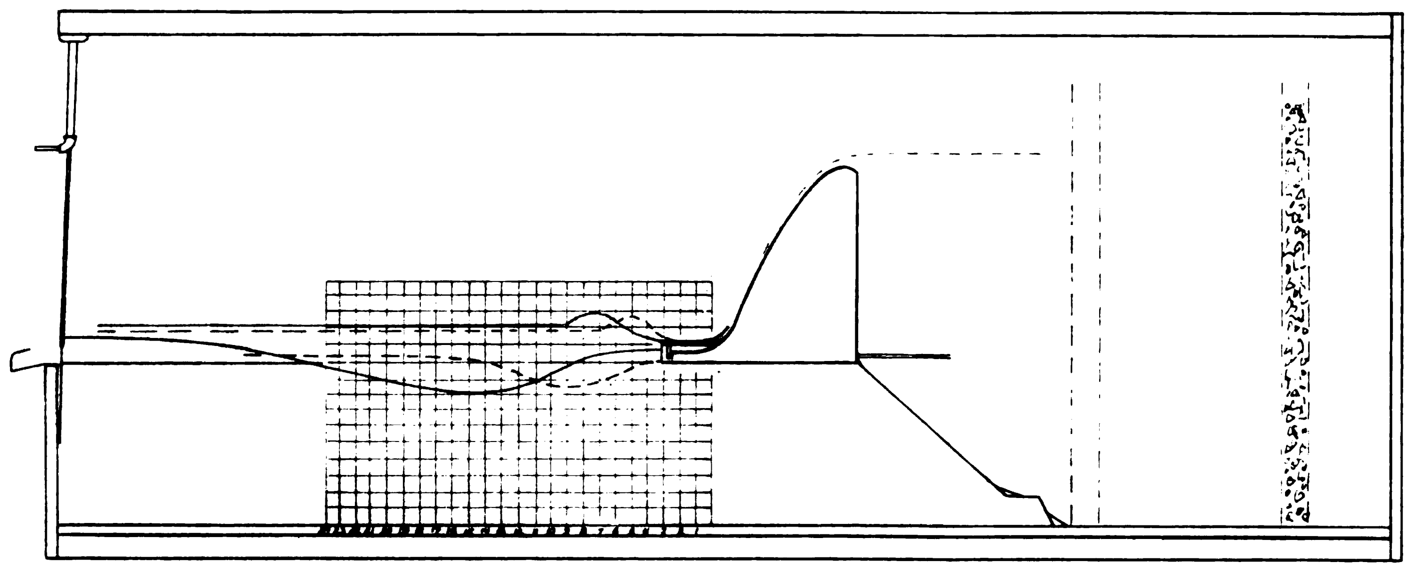


PLATE NO. 1

Quantity of Water in C.F.S. .046 to .058

Depth for Hydraulic Jump

This picture shows the effect with a plain apron and a medium head of water on the dam

Effect of a low head on the dam when the tail-water is low

as it moved farther and farther from the dam, the holes that had been formed nearer the dam were filled up by the horizontal rolling of the water. Part of the water went one way and part another. The water on top of the crest went over, then down to the level of the tail-water and on. The water on the under side of the crest, that is the water next to the apron, had a tendency to flow back along the bottom toward the dam carrying part of the eroded material with it. Thus any hole forming near the dam during a low head would be filled up when the head increased.

After considerable experimenting with the amount of water flowing, it was finally discovered why erosion occured under the apron of the dam. A very small quantity of water was allowed to flow over the dam, just enough so that instead of shooting out from the apron, the water ran over the end and dropped in to the tail-water. Although this water fell only a short distance it had enough force to start a roller action of the tail-water directly under the edge of the apron. Plate number two shows what happens. The water that rolls back under the apron stirs up the material, which is then carried away by the swifter moving water. Looking at the dam from the side shown in the plate, the water rolling back under the dam has a counter clockwise motion, and the water rolling away from the dam has a clockwise motion.

It can be easily seen that a hole under the toe of a dam caused by a long period of low water with a small flow,

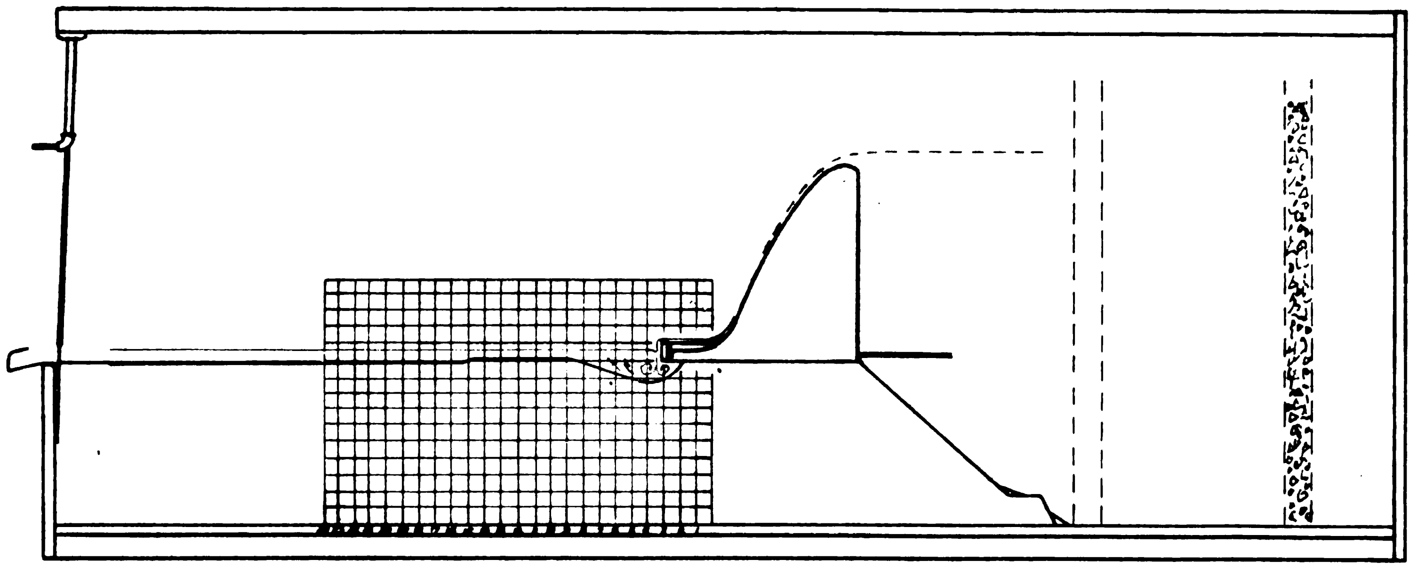


PLATE NO. 2

Quantity of Water In C.F.S. .0088

Depth for Hydraulic Jump

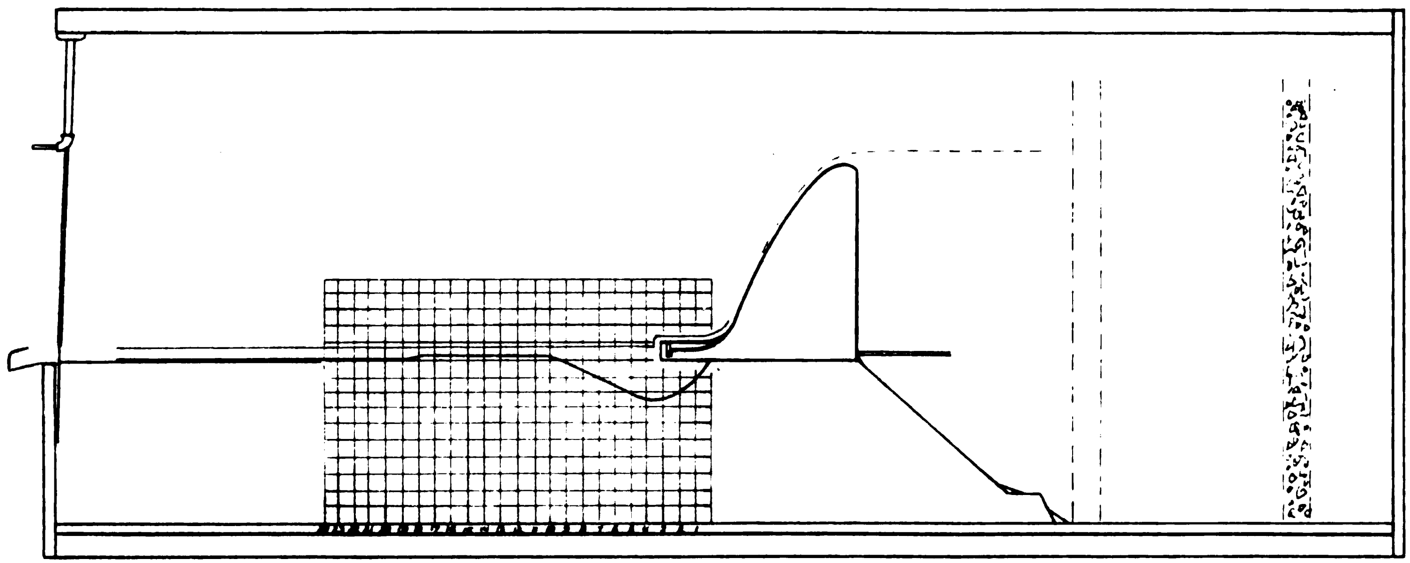


PLATE NO. 3

Quantity of Water in C.F.S. .0091

Depth for Hydraulic Jump

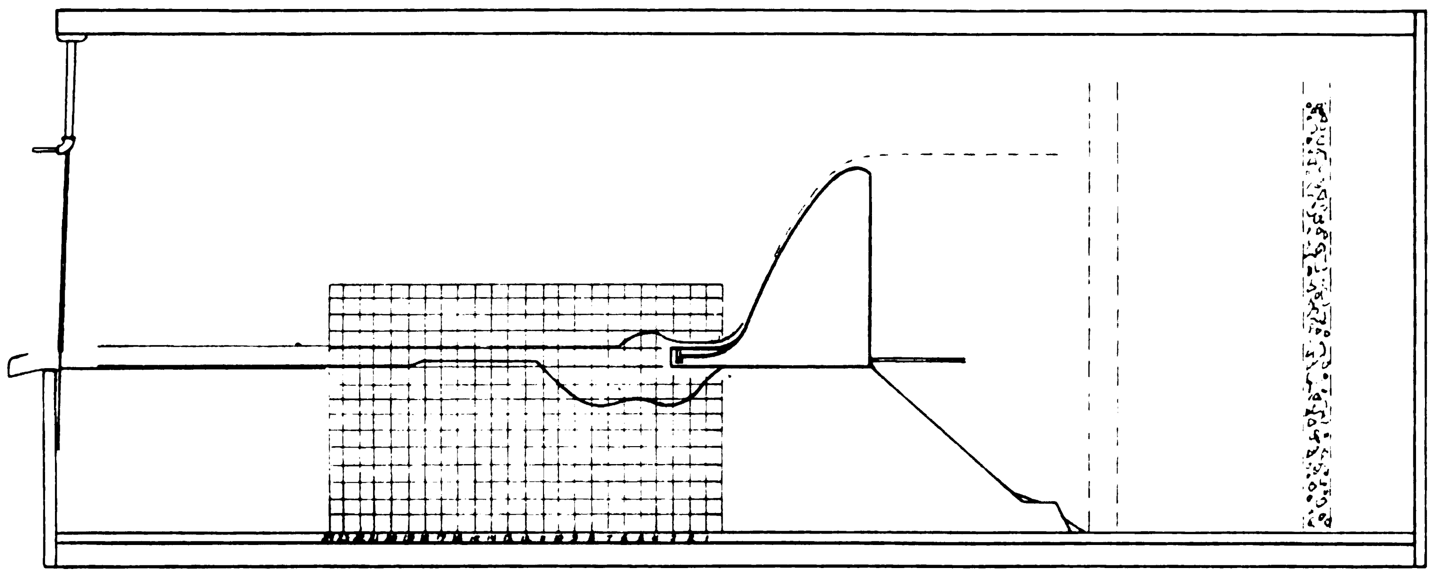


PLATE NO. 4

Quantity of Water in C.F.S. .0117

Depth for Hydraulic Jump

might be very dangerous. Should a flood period follow directly on a dry period, the dam might be pushed in to the hole, due to the lack of support at that point, and the added pressure on the dam.

Plate three shows the effect after sixteen hours of continuous flow. This shows that the amount of erosion is a factor of the time. However, after considerable time has elapsed, the erosion occurs so slowly as to be unnoticeable. After the water under the toe becomes deep enough, there is not enough disturbance on the bottom to cause very much erosion.

Plate number four shows the effect of a slight increase of flow. The erosion occurs out farther, making the hole longer. This shows that a variation of flow may cause even more damage than a steady small flow. The material is being steadily moved away from the dam.

The flow of water was increased still further. This caused erosion farther down stream from the dam and some of the eroded material was carried back and deposited in the hole formed during the small flow. In this way with varying rates of flow, the water digs out one hole at the same time that it is filling up another, and the worst part of it is that it never completely replaces the material eroded from the holes made closer to the apron. In fact, when the water changes from a large flow back to a small flow it is easier to transport the material from the nearer hole over in to the larger

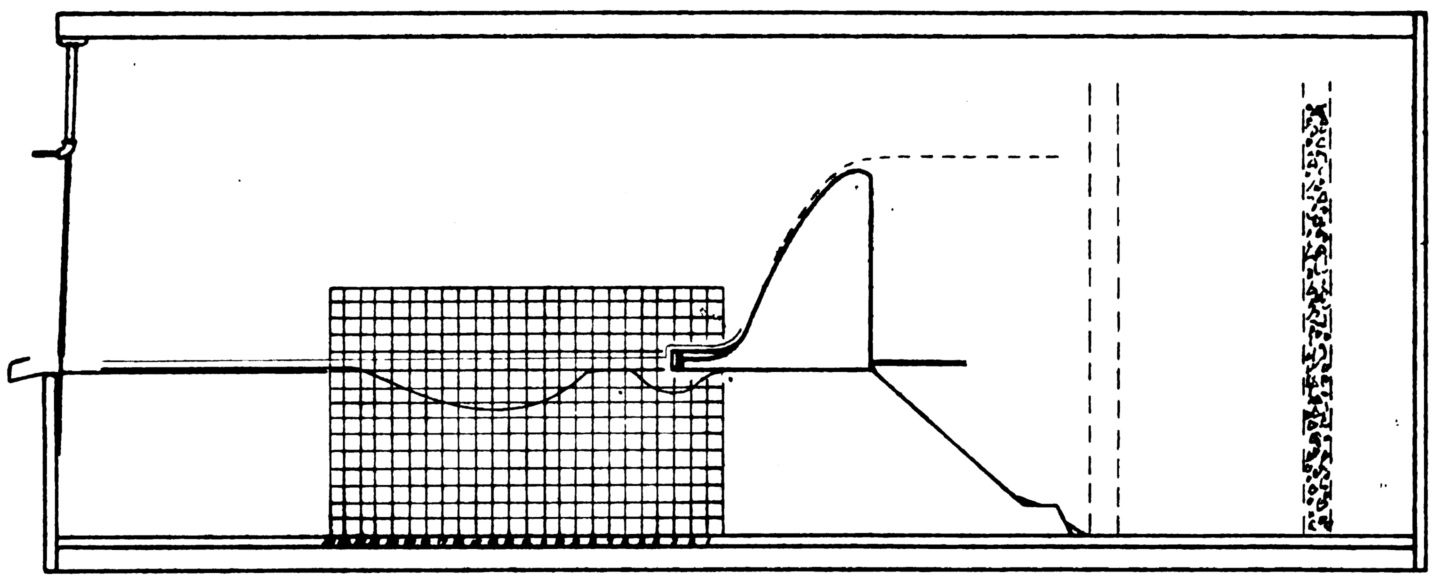


PLATE NO. 5

Quantity of Water In C.F.S. .0084

Depth for Hydraulic Jump

hole just formed a little farther down stream.

Plate five shows the effect when a light flow is preceeded by a fairly heavy flow.

The foregoing experiments point to the fact that the real damage from erosion is caused by a very small flow of water just running off the end of the apron. The problem of the small flow must not be over looked in the design of energy absorbers.

Stilling Dam Four Inches From Edge of Toe

With the stilling dam as shown in plates six, seven, and eight, a small quantity of water was allowed to flow over the dam. This was increased until a relatively large amount was flowing over the dam. As shown in plate six a small flow caused a great deal of erosion directly under the stilling dam and apron. As the flow was increased the erosion was thrown out farther. Plates seven and eight show that the hole remains under the apron when the flow is increased slowly. A little of the material is carried back, partially filling up the hole.

The water was stopped and the sand washed away from under the toe was replaced, packed down, and smoothed over. Then the water was started with a fairly large flow. Instead of eroding a hole directly under the toe, the water immediately formed a hole farther from the stilling dam. There was no erosion directly under it as shown in plate nine. The larger the flow the more erosion occurred. The dip became longer and deeper. However, there failed to occur any erosion directly under the stilling dam or apron, until an unusually large flow which it is very unlikely would occur in practice, caused a hole so large and deep that there was a slight tendency for the material to slide away from under the stilling dam.

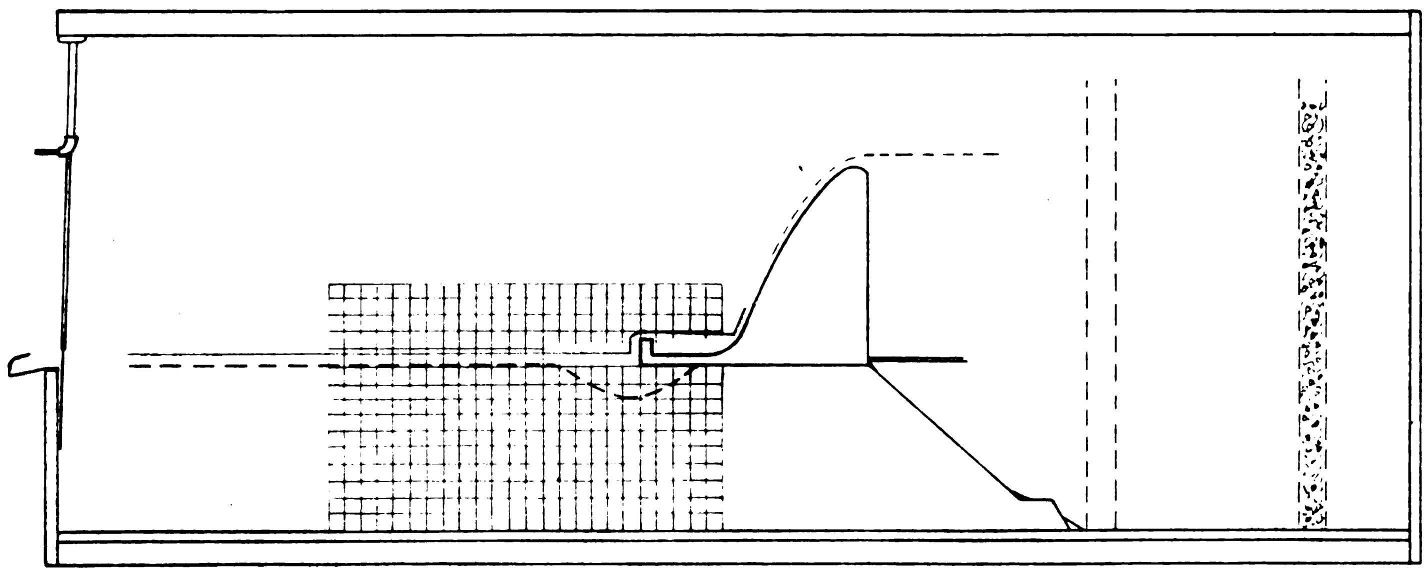


PLATE NO. 6

Ouantity of Water in C.F.S. .017

Depth for Hydraulic Jump

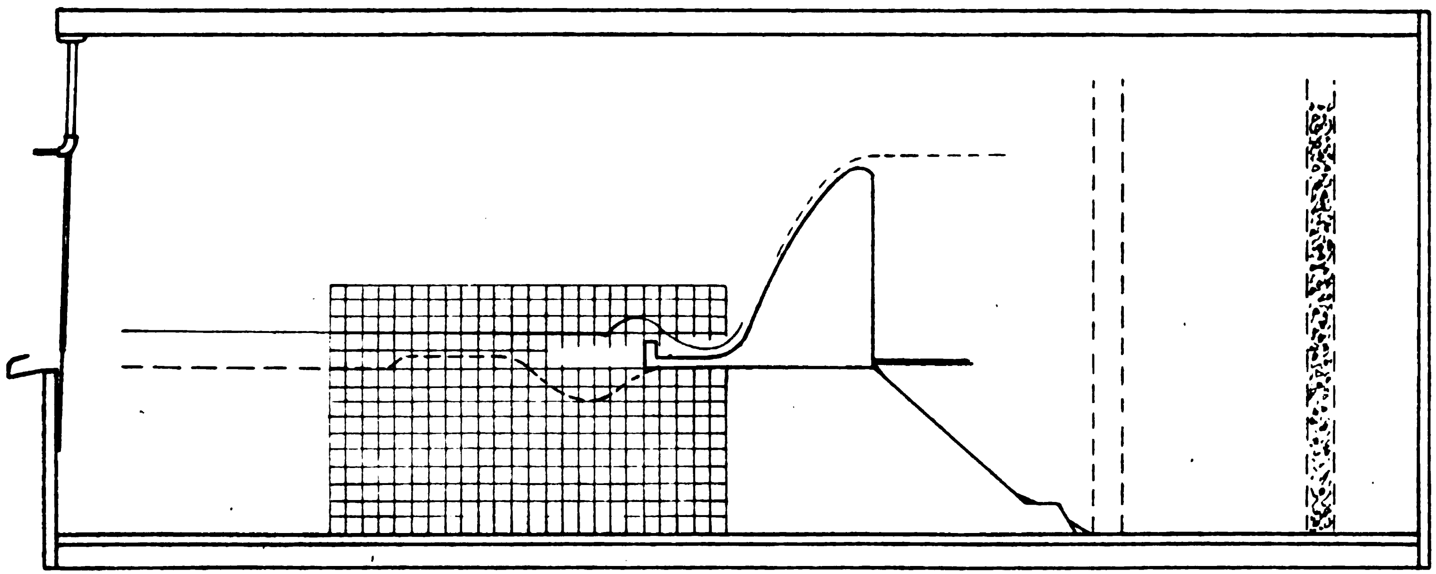


PLATE NO. 7

Quantity of Water in C.F.S. .067

Depth for Hydraulic Jump

This shows the erosion during a medium flow with the stilling dam four inches from the toe of the dam.

Shape of the erosion due to a small head after some time has elapsed.

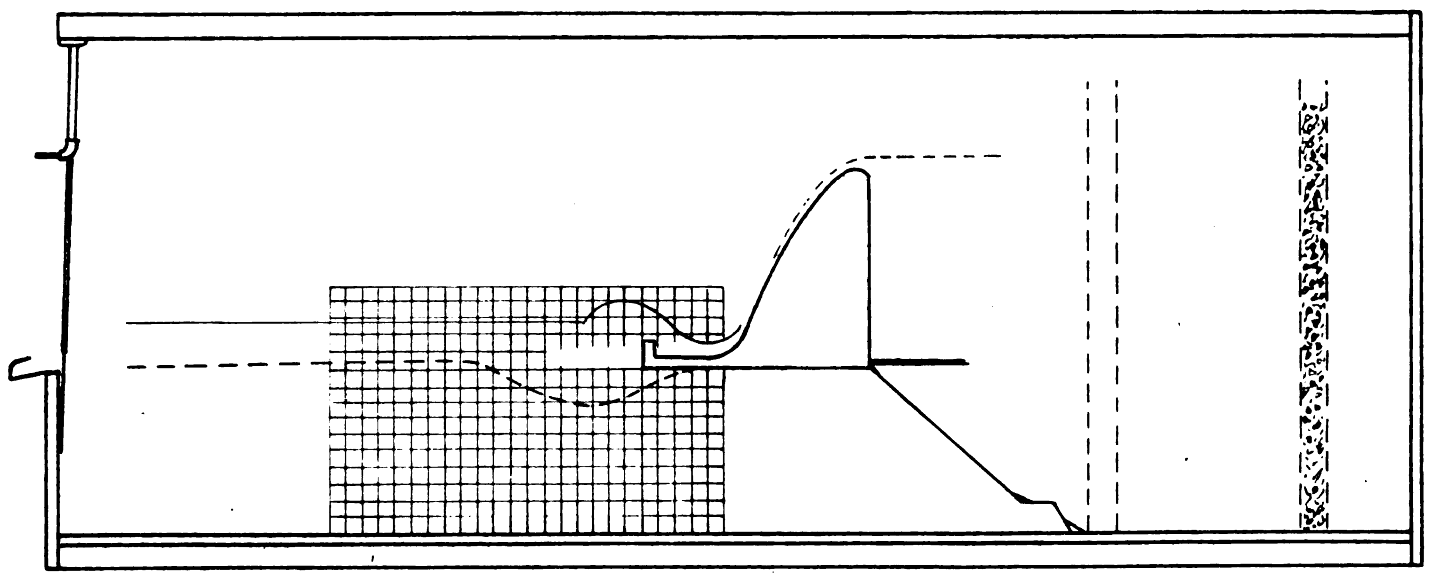


PLATE NO. 8

Quantity of Water in C.F.S. .069

Depth for Hydraulic Jump

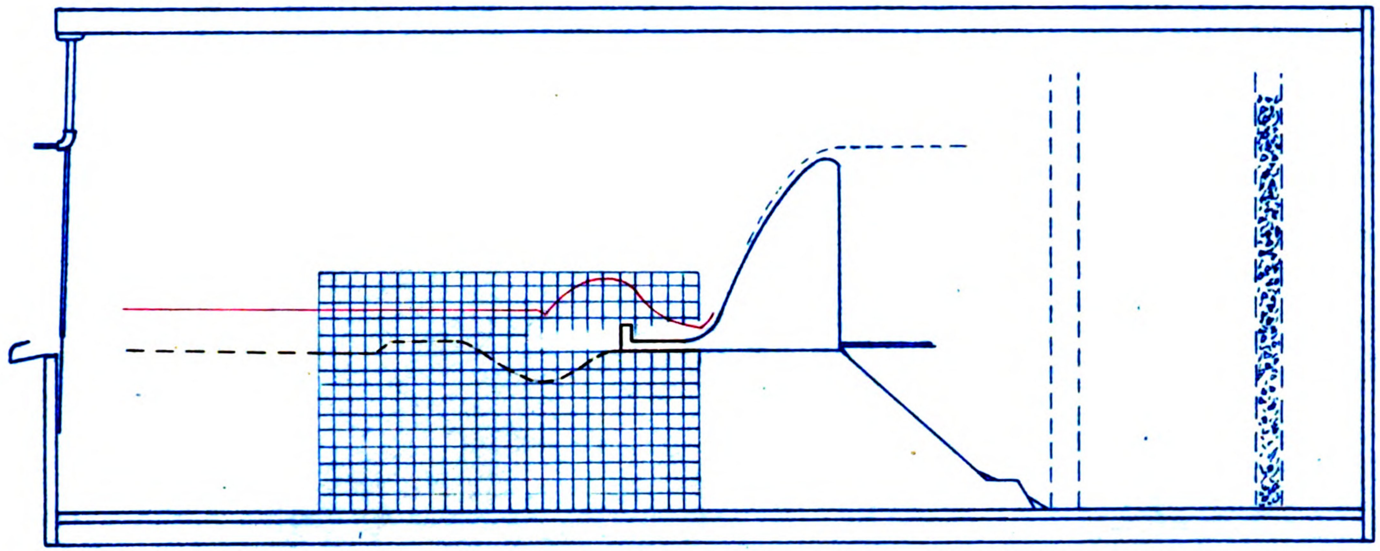


PLATE NO. 9

Quantity of Water in C.F.S. .109

Depth for Hydraulic Jump

This shows the erosion during a large head with the stilling dam four inches from the toe of the dam.

This shows the shape of the erosion when a large flow is followed by a small flow, stilling dam four inches from the edge of the toe. Note how the erosion goes back under the apron.

Stilling Dam Five Inches From Edge of Toe

The stilling dam was moved out to five inches from the point where the toe of the dam becomes tangent with the apron. Sand was then placed below the dam so that its surface was level with the top of the stilling dam. In addition, the weir at the end of the stilling dam was raised so that it gave the effect of a submerged weir placed down-stream from the dam.

As shown in plate ten there was little erosion, the erosion that occurred was very shallow. For small flows a condition of this kind would be ideal. The erosion here is of no consequence and would do little damage. The flow was increased and it was found that the erosion increased but slightly. There was one disturbing thing that occurred. Upon observation it was found that the water was gradually moving the sand in a body away from the dam, however after some time had elapsed this practically ceased. The form of the erosion became fixed.

During this experiment a peculiar thing took place. Although the flow over the dam was constant during each setting of the valve, there was a distinct oscillation, or wave formed between the stilling dam and the weir at the end of the flume. This wave looked to be a little over a foot long and continued to occur when the head was increased.

After running the water at a high head for some time, it was observed that there was practically no more erosion taking place. The flow was then cut down to a very small amount, an amount that had previously proven the cause of the most erosion. It was found to have no effect on the erosion already formed. The shape remained the same.

The water was then turned completely off and allowed to set until the river bed below the dam was completely dry. Again the water was turned on, this time to a small flow at first then increased from a small flow to a large flow, each stage of the increase being allowed to come to a stable condition. Observation showed that in no case was the erosion as bad as where the tail-water was not held back by a weir. During part of the flow there was a small amount of erosion directly below the stilling dam as shown in plate twelve. Nothing serious occurred, and there was no erosion under the apron.

However, to produce the foregoing results in practice would necessitate considerable added expenditure in construction of the dam. The dam would have to be built lower. Also the weir built a short ways down-stream from the dam would add to the expenditure. A stilling dam should also be built to take care of large flows. The high level of the tail-water is the reason for the small amount of erosion.

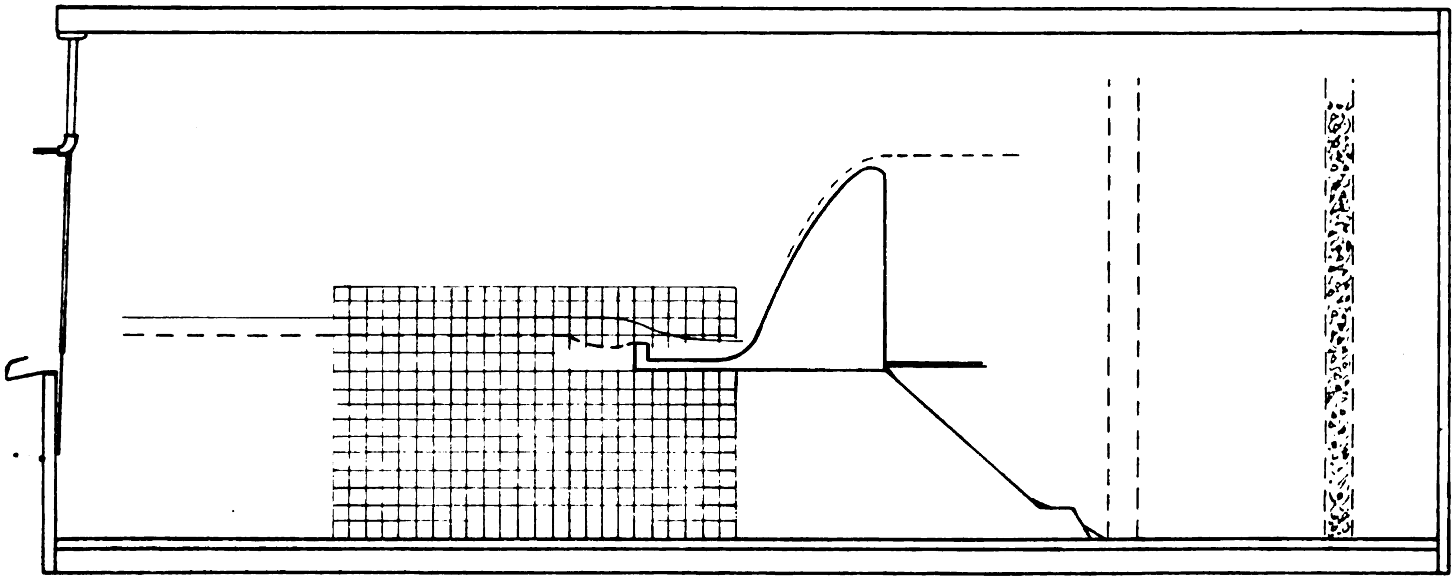


PLATE NO. 10

Quantity of Water in C.F.S. .046

Depth for Hydraulic Jump

This shows the stilling dam five inches from the toe with a small flow and high tail-water

The effect of a large flow with high tail-water

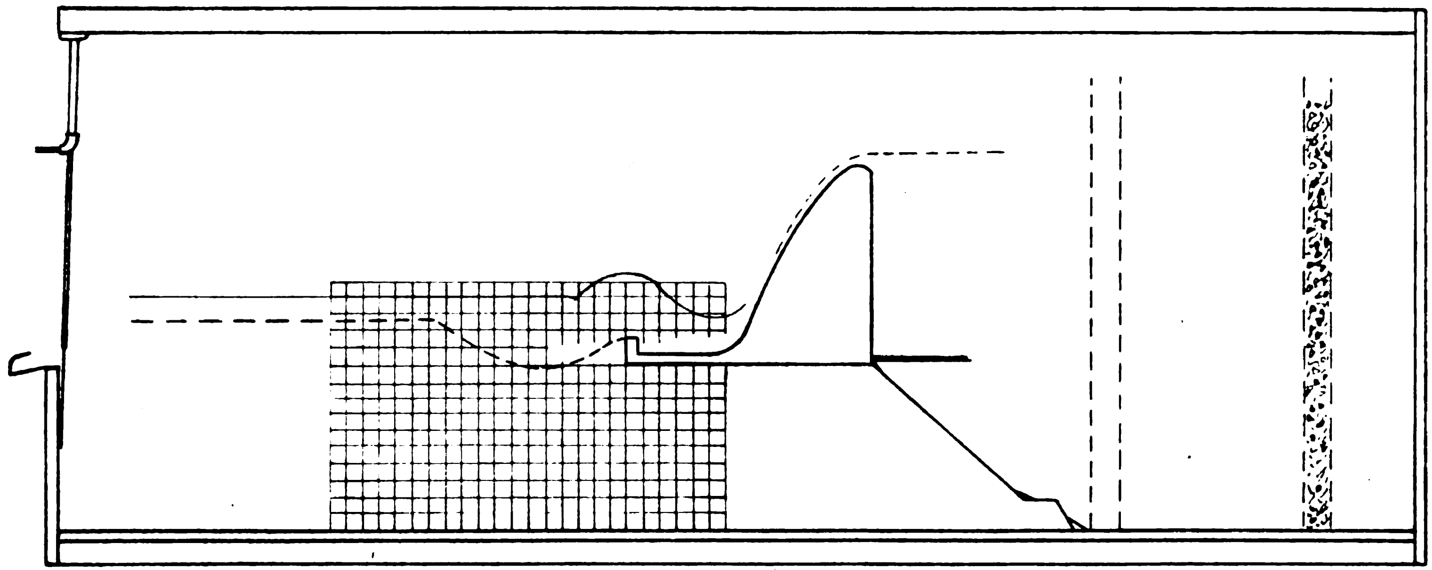


PLATE NO. 11

Quantity of Water in C.F.S. .121

Depth for Hydraulic Jump

This shows the effect of a small flow following a large flow when the level of the tail-water is high. The excessive height of the tail-water is the only thing that prevents erosion. Had the level of the tail-water been low, the erosion would have gone under the apron.

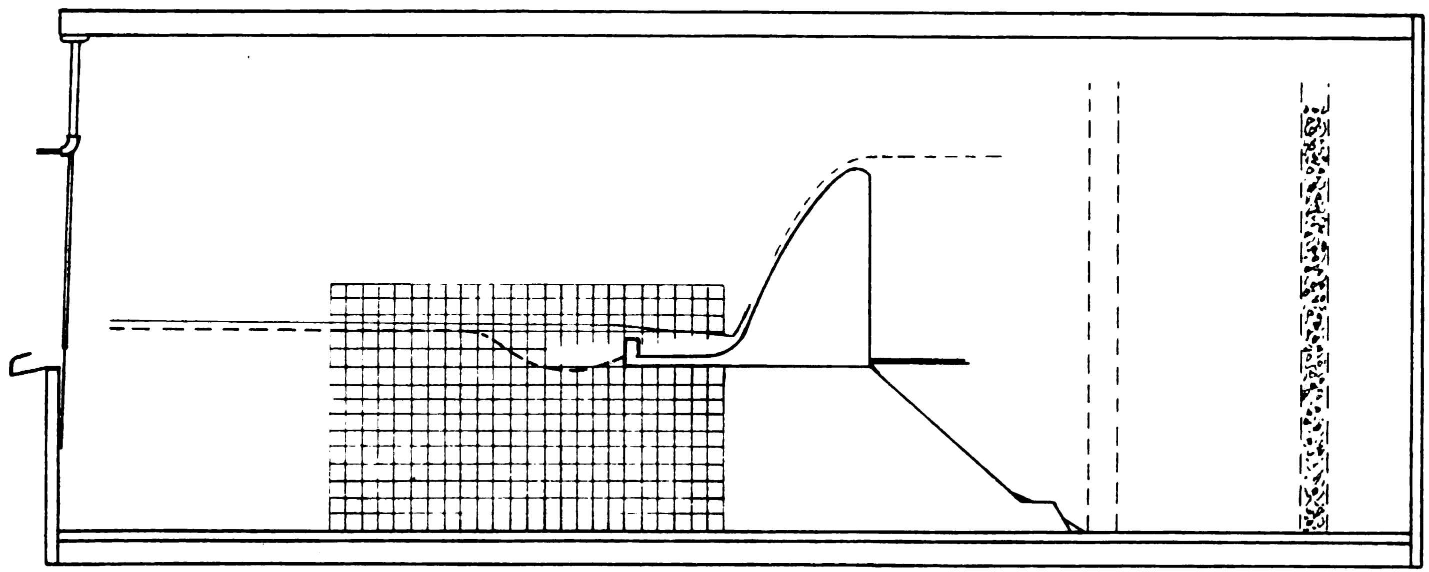


PLATE NO. 12

Quantity of Water in C.F.S. .042

Depth for Hydraulic Jump

Stilling Dam Six Inches from Toe

With the stilling dam placed six inches from the edge of the toe, the water was started over the dam with a low flow. As in the previous tests the erosion occurred close to the stilling dam. As the head on the dam increased the erosion moved out farther away from the stilling dam, and some of the material was carried back by the currents on the bottom and deposited under the edge of the stilling dam as shown in plate number thirteen. Regarding the depth of tail-water, the same is true as of the other types of stilling devices, the deeper the tail-water the less the erosion.

After the water had reached a high flow, and had remained there long enough for conditions to become constant, the flow was gradually reduced to a small flow. Plate number fourteen shows what takes place. The erosion goes under the apron. The material that was built up has now been carried in to the hole formed during the large flow.

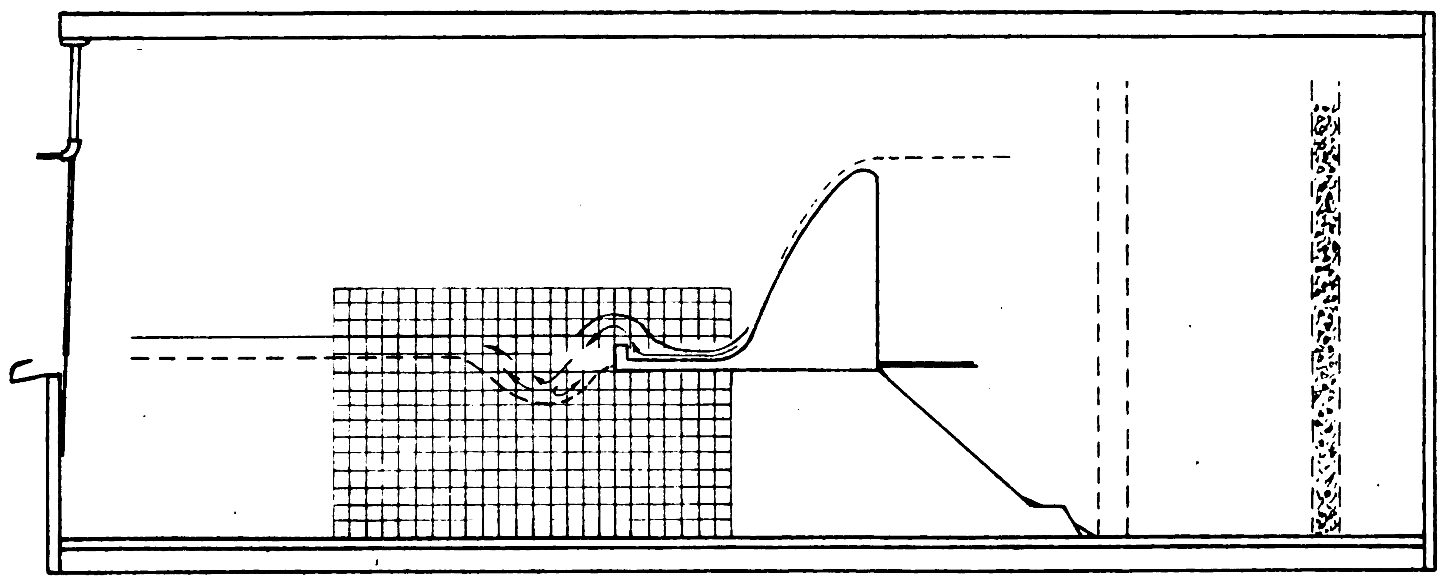
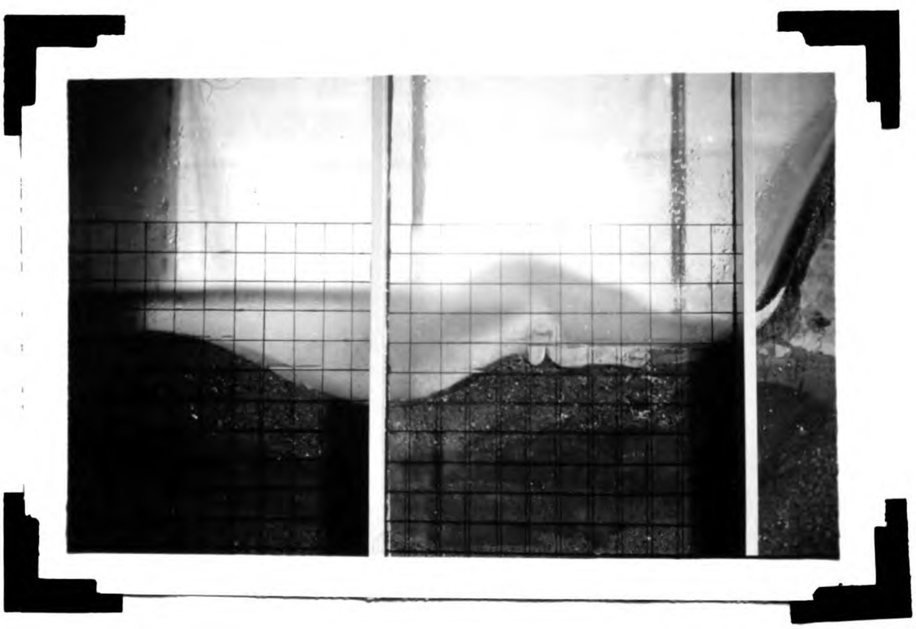


PLATE NO. 13

Quantity of Water in C.F.S. .093

Depth for Hydraulic Jump

Stilling dam six inches from the toe with a small head and low tail-water



Stilling dam same as above with a high head and medium depth of tail-water

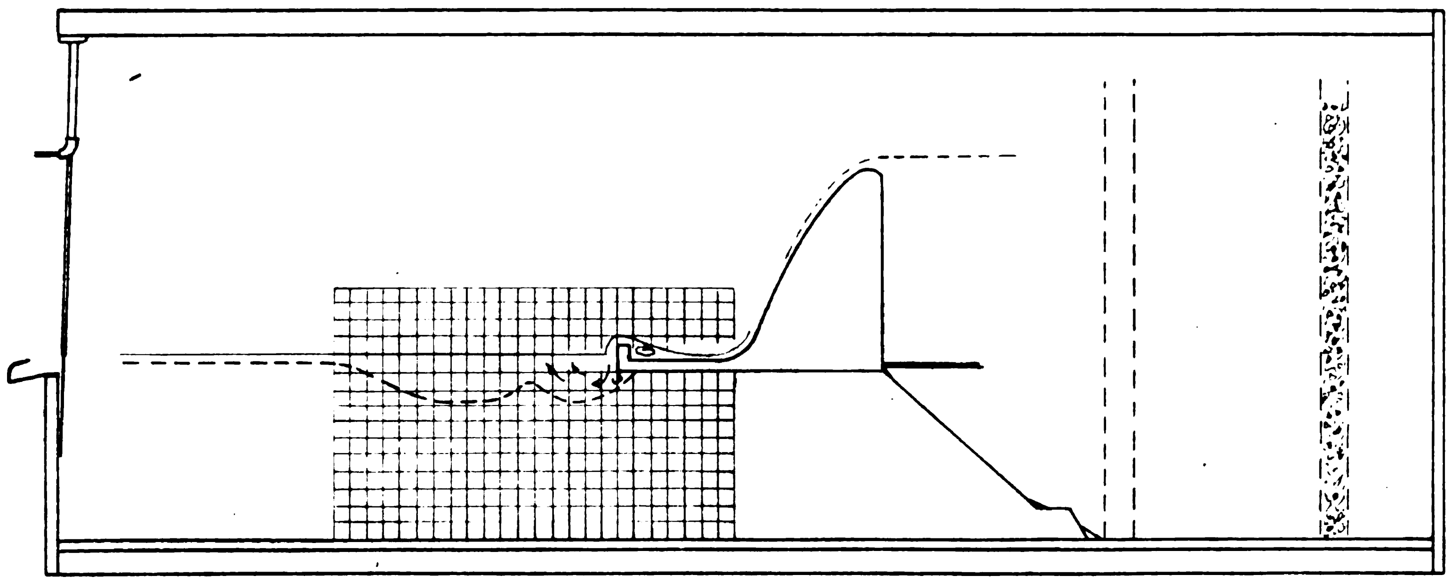


PLATE NO. 14

Quantity of Water in C.F.S. .052

Depth for Hydraulic Jump

Effect of a small flow following a large flow, note how the erosion has moved toward the stilling dam

Stilling Dam Seven Inches from Toe

With the stilling dam placed seven inches from the edge of the toe, the action was the same as when the stilling dam was six inches from the toe except for one thing, the water was held back more on the apron, which caused a slight decrease in the erosion. The reason the water was held back was because the stilling dam being placed out farther held more water on the apron, which caused more resistance for the incoming water. Plate number fifteen shows a high flow going over the dam.

When the flow was reduced to a small amount, the erosion occurred under the apron as in the preceeding tests. Plate mumber sixteen shows the effect of a low flow.

Stilling Dam Eight Inches from Toe

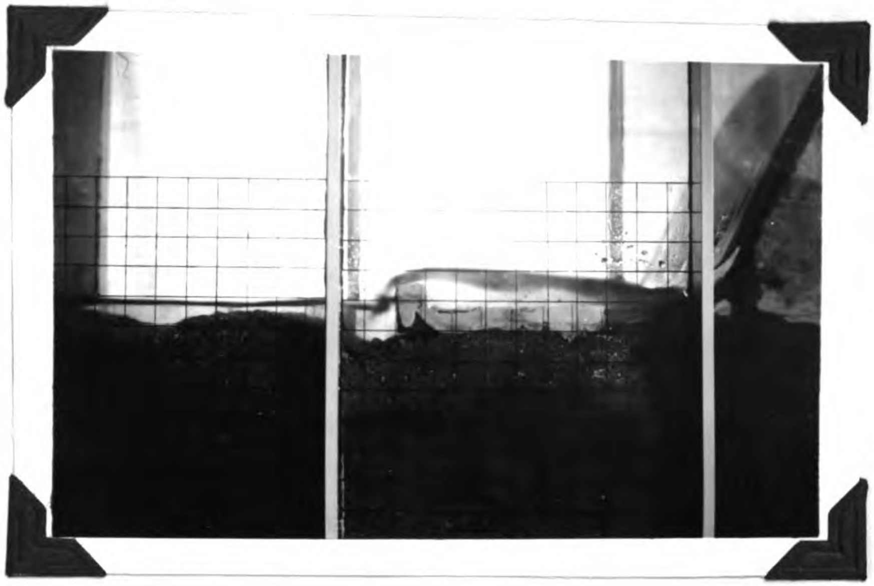
The effect of the stilling dam eight inches from the toe is the same as at seven inches except that there is less erosion. The stilling dam holds back more water on the apron and makes more resistance for the incoming water. More water rolls back on top. When a large flow was succeeded by a small flow, the water eroded under the apron.

Stilling Dam Nine Inches from Toe

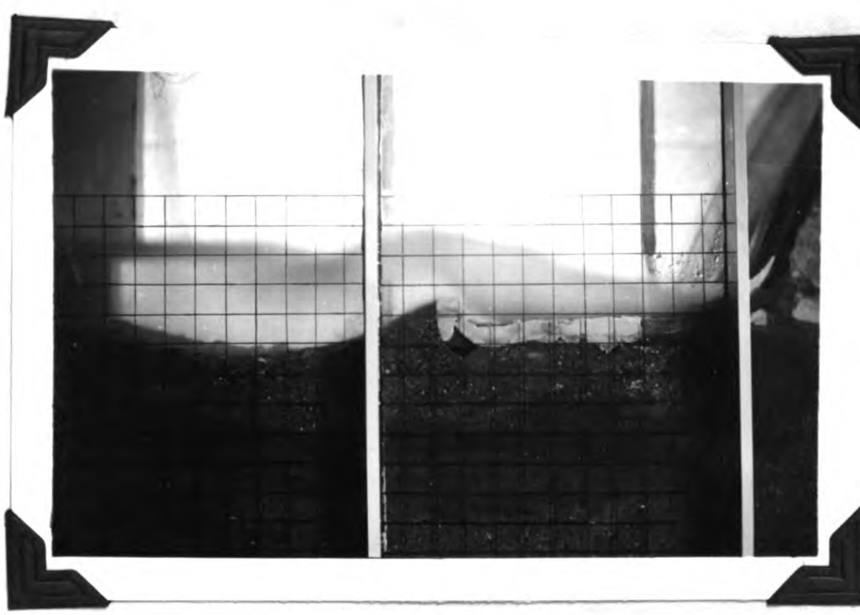
The same occurs here as in the preceeding tests. Each time the stilling dam is moved out there is less erosion except at the very small heads where the water erodes under the

apron. At this distance from the edge of the toe the erosion is a minimum at all heads except those that are very low. The erosion at very low heads is the same for all distances of the stilling dam from the edge of the toe. Plate number seventeen shows the erosion with the stilling dam out nine inches from the dam. The sand was leveled off even with the top of the stilling dam before the test was begun.

Plate number eithteen shows the effect of a low flow succeeding a high flow. It is the shifting back and forth in practice between a high flow and a low flow that causes serious erosion. If the flow were fairly constant over a dam, an energy absorber could be designed that would prevent erosion. However, this eroding under the apron, as pointed out before, can be practically eliminated by keeping the level of the tail-water up. In plate number eighteen the erosion shown close to the stilling dam did not occur when the tail-water was up level with the top of the stilling dam. If the level of the river bed always stayed up high enough to keep the tail-water at the proper level there would be no erosion under the stilling dam or apron.



Stilling dam nine inches from the toe during a small flow with medium depth of tail-water



Effect during a large flow. The erosion is a minimum with the stilling dam at this distance from the toe. There is no advantage in placing the stilling dam beyond nine inches from the toe.

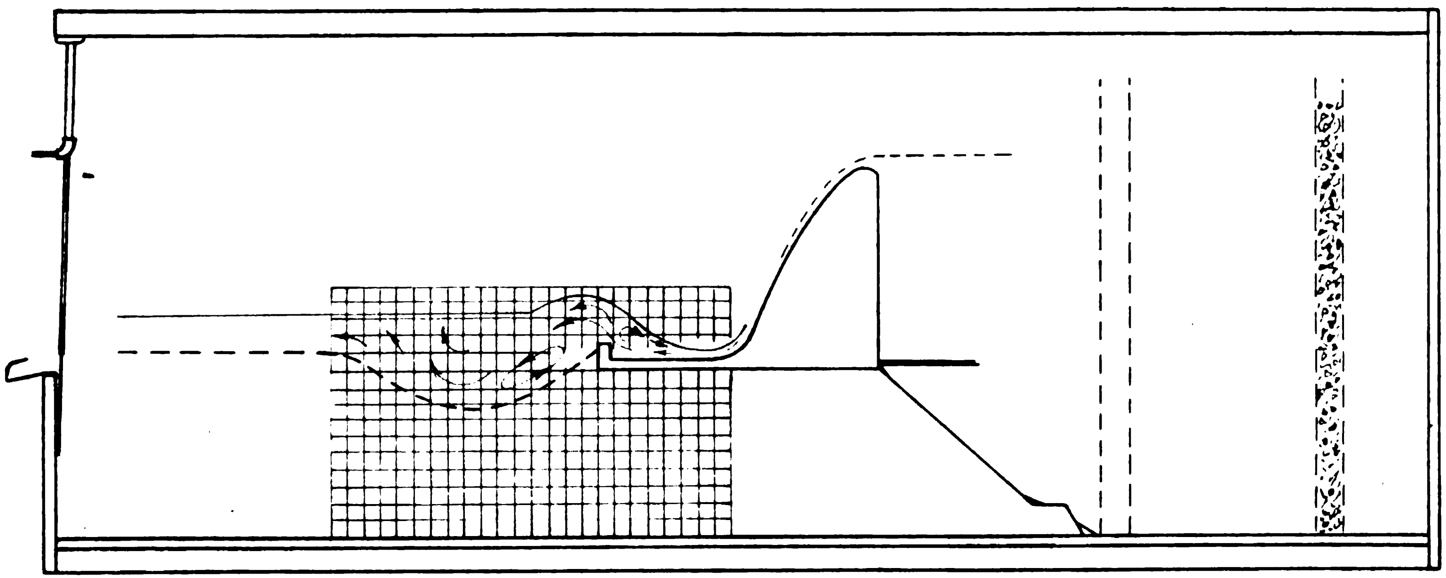


PLATE NO. 15

Quantity of Water in C.F.S. ..184

Depth for Hydraulic Jump

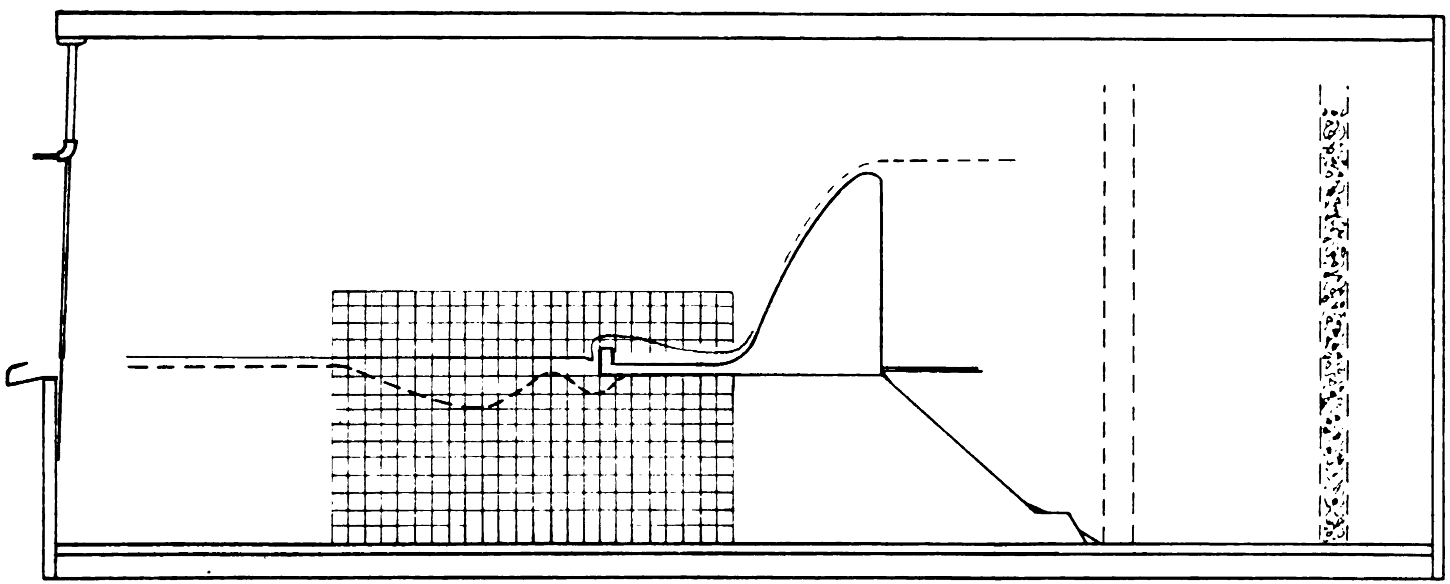


PLATE NO. 16

Quantity of Water in C.F.S. .028

Depth for Hydraulic Jump

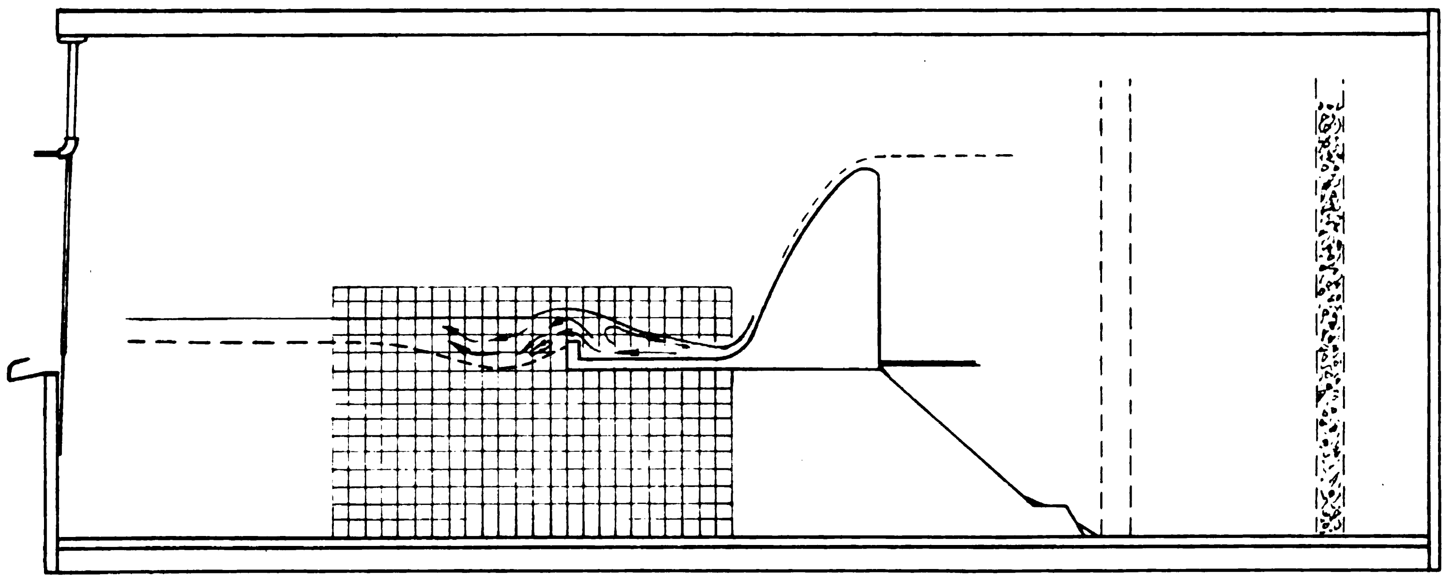


PLATE NO. 17

Quantity of Water in C.F.S. .156

Depth for Hydraulic Jump

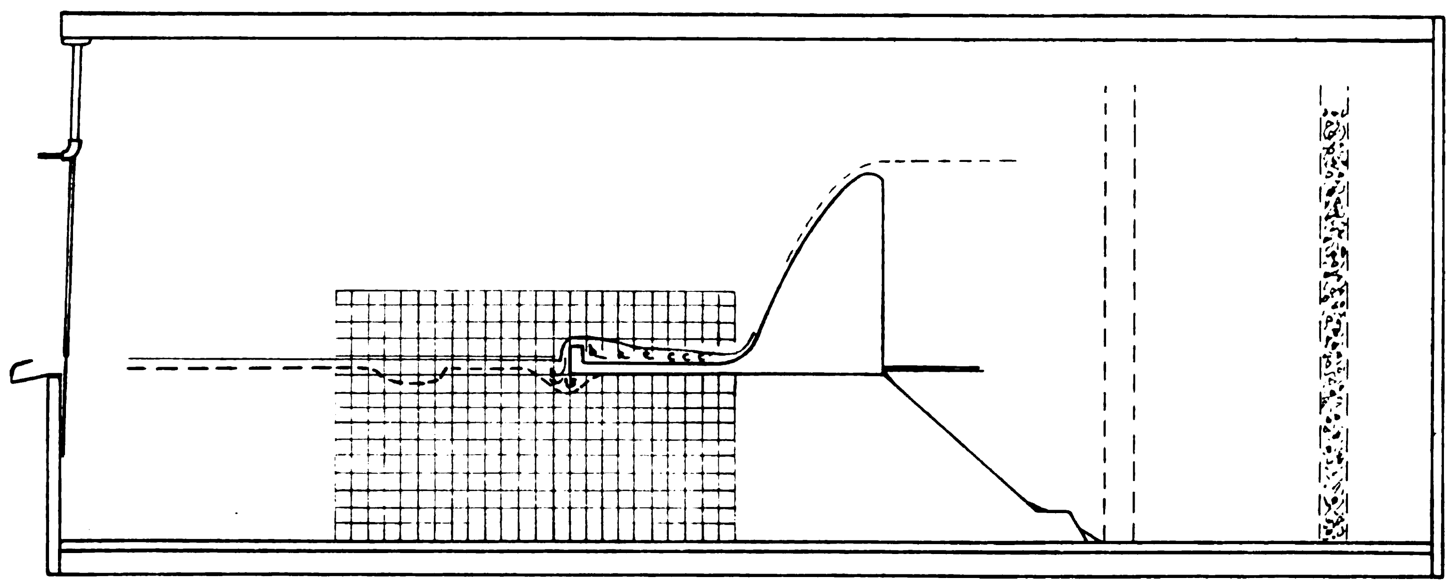


PLATE NO. 18

Quantity of Water in C.F.S. .023

Depth for Hydraulic Jump

Stilling Dam Slanted Forward

One of the advantages of the model is that practically any conceivable type, or shape of energy absorber may be easily made and quickly fastened on the apron. For the particular experiment described here, a galvanized sheet iron stilling dam, was fashioned in such a way that the forward face slanted toward the dam at an angle of sixty degrees with the horizontal and the down stream face made parallel to the forward face. In addition the down stream face extended down below the bottom edge of the apron, and then curved out below the surface of the tail-water.

This type of stilling dam proved very effective during a small flow. The force of the water was checked by the sharp edge of the stilling dam, and the water flowing down the lower edge of the stilling dam was deflected in a horizontal direction so that there was very little erosion, infact there was no erosion under the stilling dam.

In changing from a low flow to a high flow, there was a point at which the upper edge of the stilling dam failed to completely check the force of the incoming water. Instead of flowing down the lower face of the stilling dam, the water simply shot over it and down in to the tail-water. The material under the edge of the stilling dam had a tendency to slide in to the hole formed.

Plate nineteen shows the effect during a small flow. From the result of experiments, it appears that the incoming water does the least damage when it discharges in a horizontal or slightly upward direction under the surface of the tail-water. Raising the level of the tail-water, which is the same as lowering the dam or placing a weir some distance down stream, decreases the erosion at the toe regardless of the type of energy absorber used.

Plate number twenty shows the effect of a slightly increased flow. The water is flowing over the stilling dam so fast that it leaves the down stream face and falls in to the tail-water at an angle of approximately sixty degrees. The stilling dam does not completely destroy the energy of the incoming water. Increasing the head causes the erosion to go deeper and farther back under the stilling dam. Plate number twenty-one shows the action of extremely high heads. The water shoots over the stilling dam and is not turned back at all. One of the reasons for the successful operation of this type of stilling dam during a low flow is the fact that the water was made to reverse its direction on the apron, thus absorbing the energy of the water. Plate number nineteen shows what takes place.

Stilling dam inclined sixty degrees toward the dam with a suppressed apron below it. This shows the effect during a small flow with medium depth of tail-water.

Stilling dam as above with a large flow and ordinary depth of tail-water

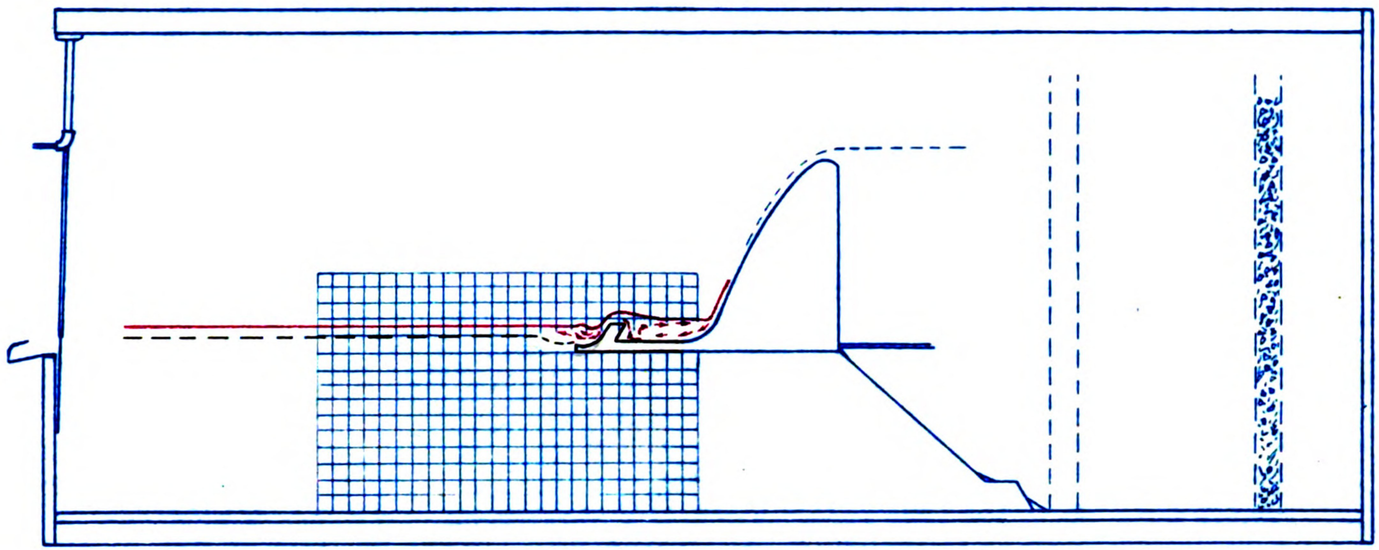


PLATE NO. 19

Quantity of Water in C.F.S. .030

Depth for Hydraulic Jump

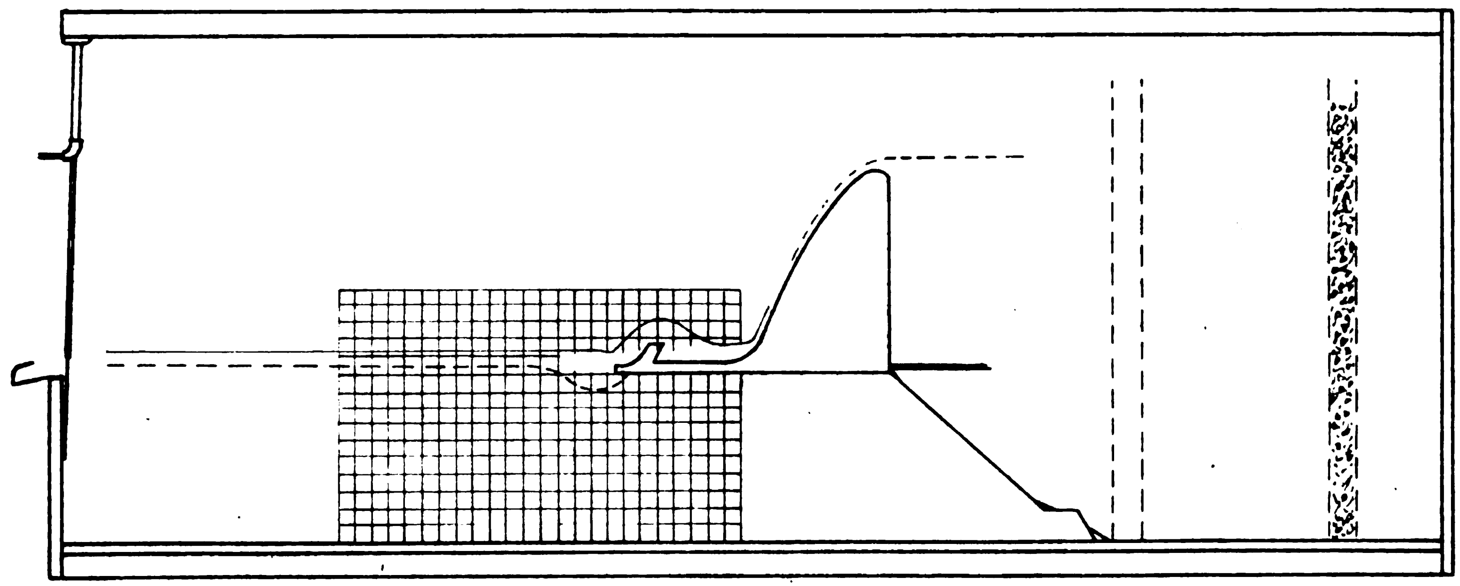


PLATE NO. 20

Quantity of Water in C.F.S. .082

Depth for Hydraulic Jump

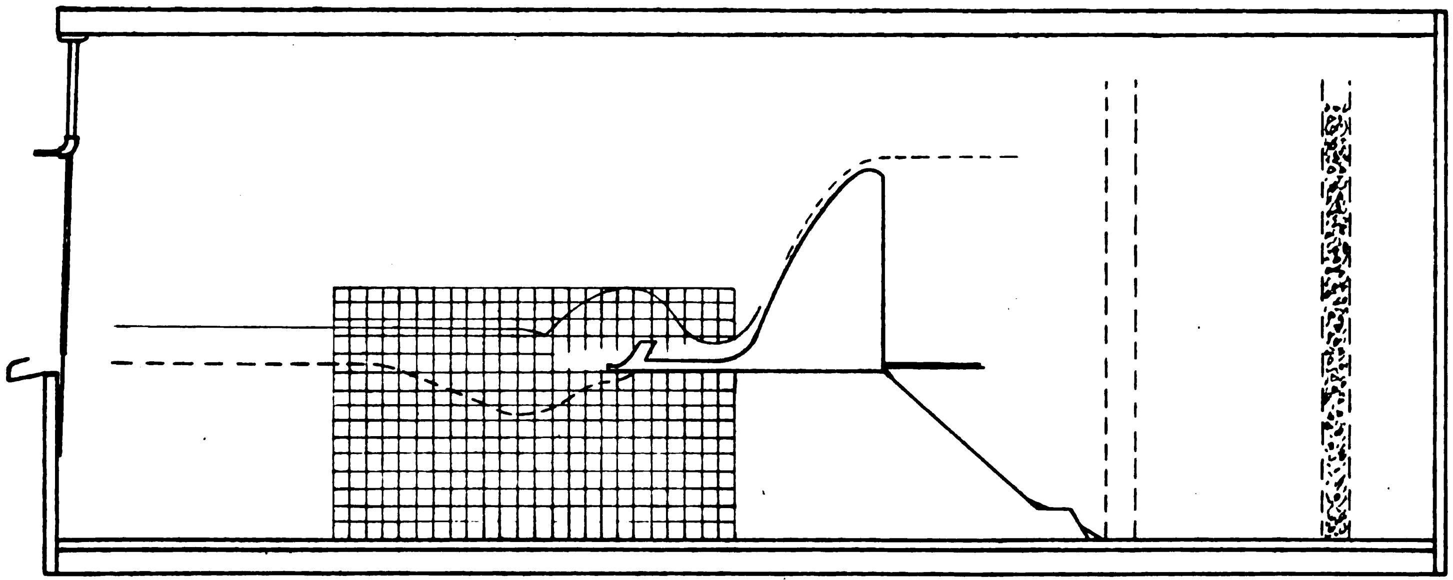


PLATE NO. 21

Quantity of Water in C.F.S. .195

Depth for Hydraulic Jump

Laminated Stilling Dam

A stilling dam was fashioned with a small ridge placed about three-fourths of an inch in front of a larger and wider ridge. Where the water dropped over the second ridge, a short apron curved up under the tail-water. Plate twenty-two shows the shape of the stilling dam, and also what takes place during a small flow.

The action is similar to that of the other types of stilling dams. The water flows back on the apron, thus destroying the force of the incoming water. It flows down the face of the stilling dam and on to the short apron, where it is then directed up under the surface of the tail-water.

A slight increase in flow produced surprising results as shown in plate number twenty-three. The incoming water traveled in a thin smooth sheet along the apron until it reached the stilling dam. Here it shot up in to the air half as high as the dam and landed in the tail-water. Erosion took place at the point where it landed about two inches from the short apron of the stilling dam. Increasing the head had no effect on the action except to make it worse. The water shot up a little higher, caused the erosion to go a little deeper, and caused more agitation of the tail-water.

Raising the level of the tail-water diminished the erosion slightly. The water did not shoot up so high and had a tendency to flow back on top of the incoming water on the

apron, causing it to boil. Of all the stilling dams experimented on up to now, this was the least effective.

This shows the effect of a laminated stilling dam during a small flow with an ordinary depth of tail-water.

This shows the same stilling dam during a large flow. Note how the water shoots into the air after leaving the stilling dam.

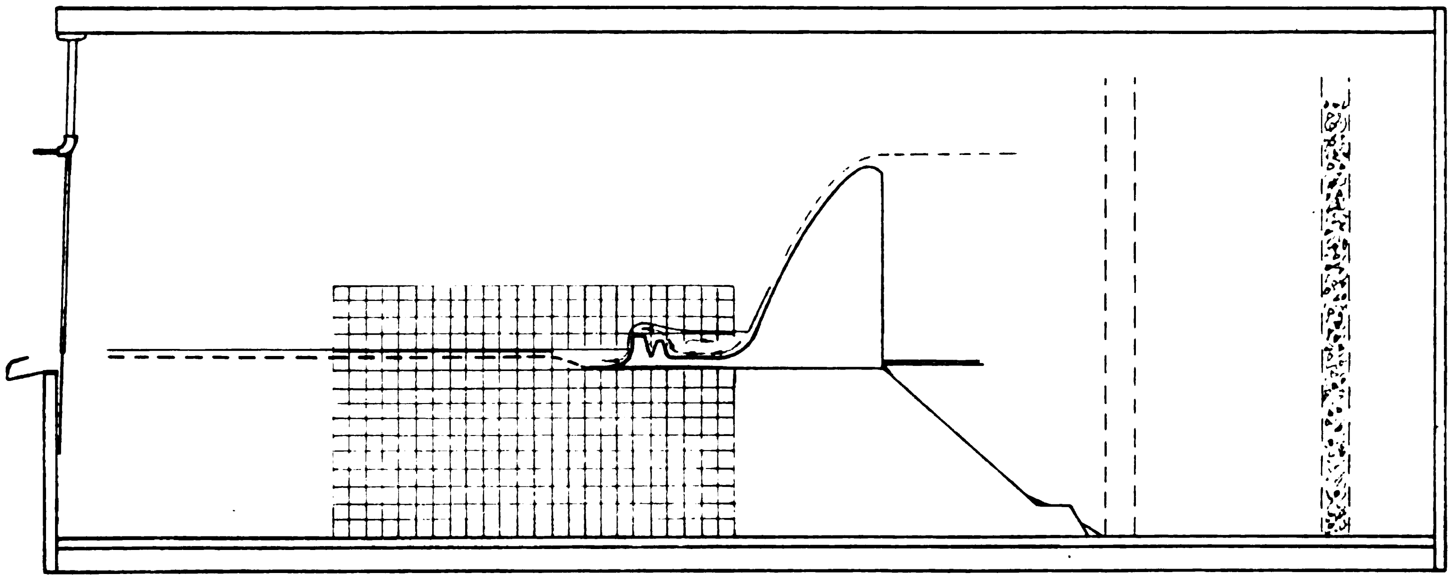


PLATE NO. 22

Quantity of Water in C.F.S. .020

Depth for Hydraulic Jump

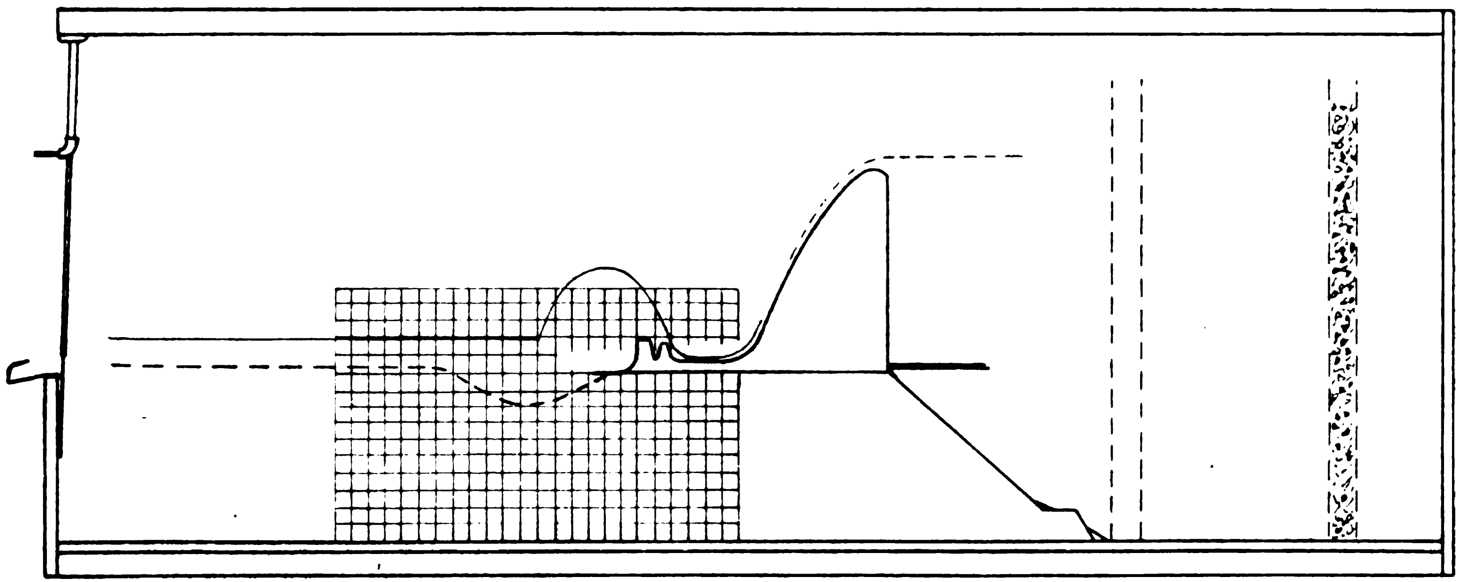


PLATE NO. 23

Quantity of Water in C.F.S. .074

Depth for Hydraulic Jump

Inclined Stilling Dam, Ridge, and Pool

In one of the previous tests it was observed that better results were obtained when a certain combination of stilling devices were reversed in order. This gave birth to the idea of the inclined stilling dam and pool described here.

A stilling dam was placed up close to the edge of the toe. This was done with the idea of throwing the water closer in as it left the stilling dam. A ridge was then placed on the apron two inches from the stilling dam. This caused the water to fall in to the pool directly below it at a certain angle. Although this ridge was not entirely essential it helped check the water from the first stilling dam.

During low flows, no erosion took place. The water after striking the first stilling dam was deflected nearly straight up accompanied by considerable boiling. The water fell against the ridge and then in to the pool directly below it. Due to the shape of the bottom of the pool the water was deflected upward under the surface of the tail-water. The erosion was practically negligible.

When the flow was increased there was very little increase in the erosion as shown in plate number twenty-four.

When the flow was increased to what would be a relatively enormous flow over a dam in actual practice the results were very gratifying. The extent of the erosion can be seen in plate twenty-five. There was considerable difference in the flow for plate twenty-four and twenty-five yet the difference

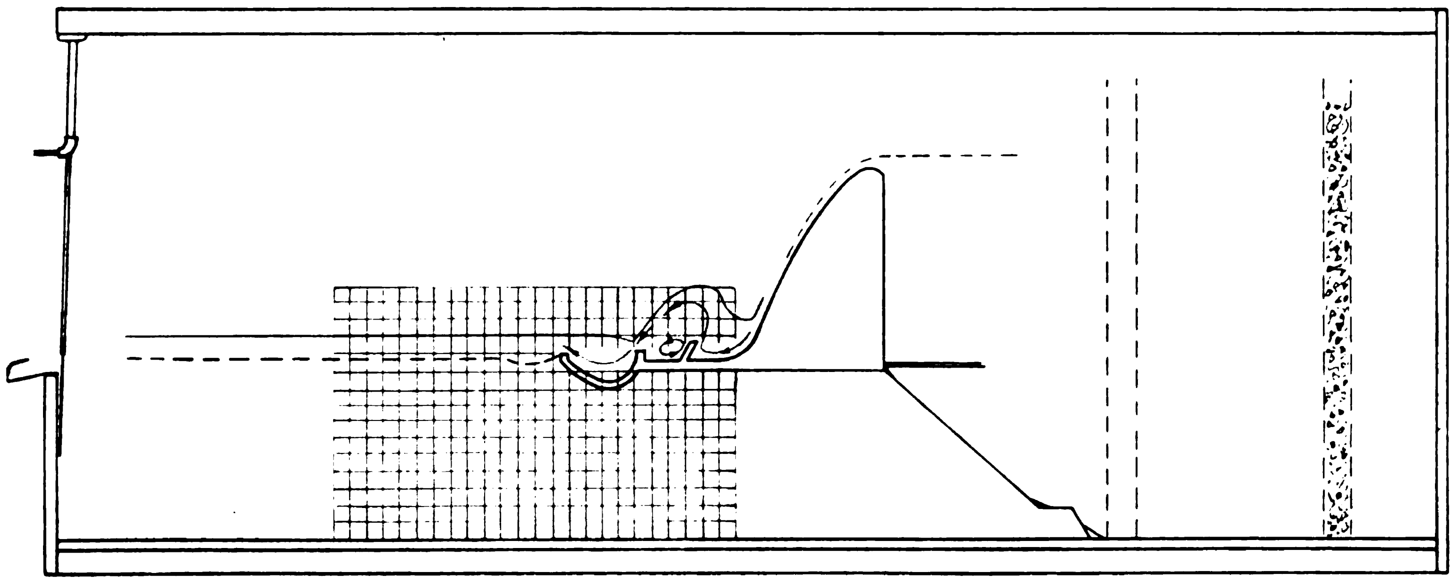


PLATE NO. 24

Quantity of Water in C.F.S. .112

Depth for Hydraulic Jump

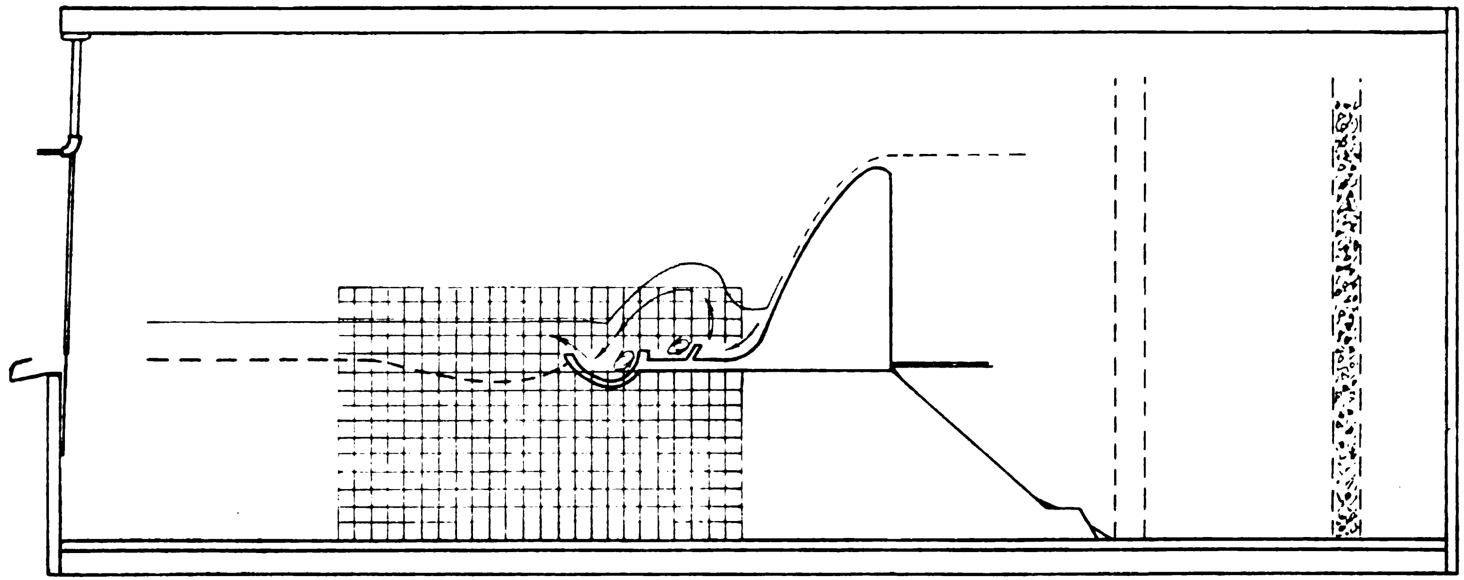


PLATE NO. 25

Ouantity of Water in C.F.S. .203

Depth for Hydraulic Jump

This shows the stilling dam inclined sixty degrees toward the main dam with a ridge and pool below it. There is a small head and ordinary tail-water depth

Stilling dam, ridge, and pool same as above with a high head and medium tail-water in the erosion is very small.

In extremely large heads the erosion that does occur although comparatively very small could be checked to a great extent by making the stilling pool at the edge of the ridge longer and deeper. Considering everything, this is the most successful combination of stilling devices for absorbing the energy of the incoming water yet devised. It remains to perfect the exact shape.

Keeping the idea of simplicity of design foremost in mind, and with the results of the preceeding experiment, an inclined stilling dam was designed with a stilling pool directly below. The stilling dam was inclined toward the main dam at an angle of sixty degrees with the horizontal. The downstream face of the stilling dam was parallel to the other face and dropped in to the stilling pool. The bottom of the pool was .9 of an inch below the surface of the apron where it joined the edge of the toe, and was six inches long.

During low flows there was no erosion, and as the head on the dam was increased there was still very little erosion. Plate number twenty-six shows the shape of the stilling dam and pool, and the erosion during a moderate flow. The path of the water is indicated by the lines with the arrows. The stilling dam absorbes a great deal of the energy of the incoming water. It also directs the water in such a manner that the energy left may be distributed over a larger area in the still-

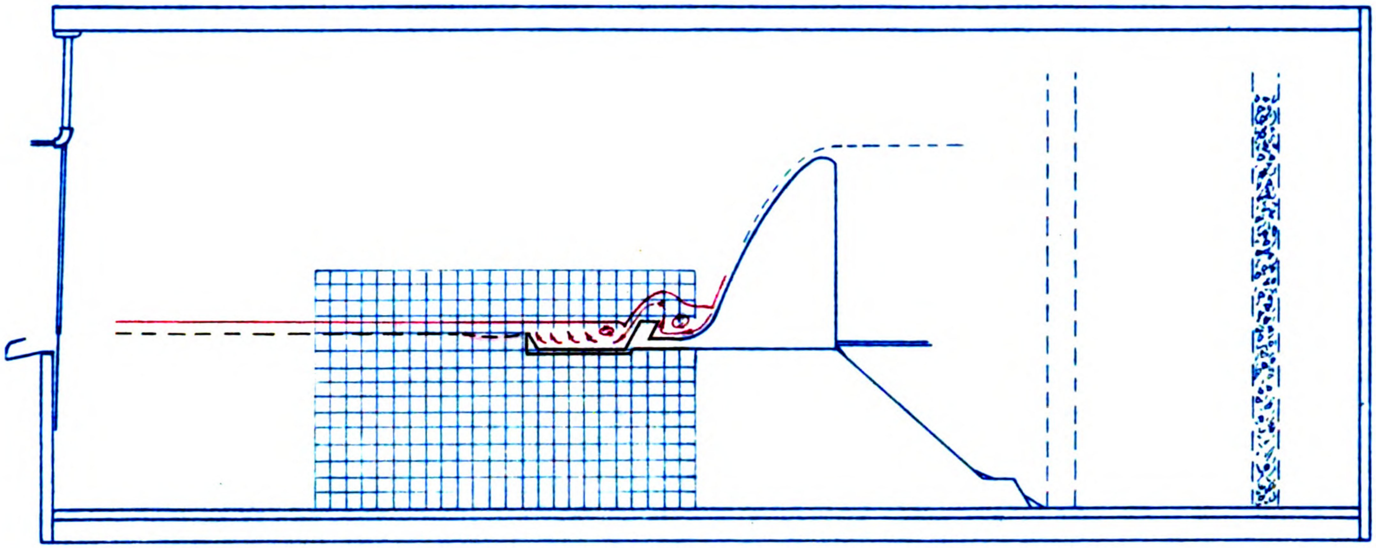


PLATE NO. 26

Quantity of Water in C.F.S. .046

Depth for Hydraulic Jump

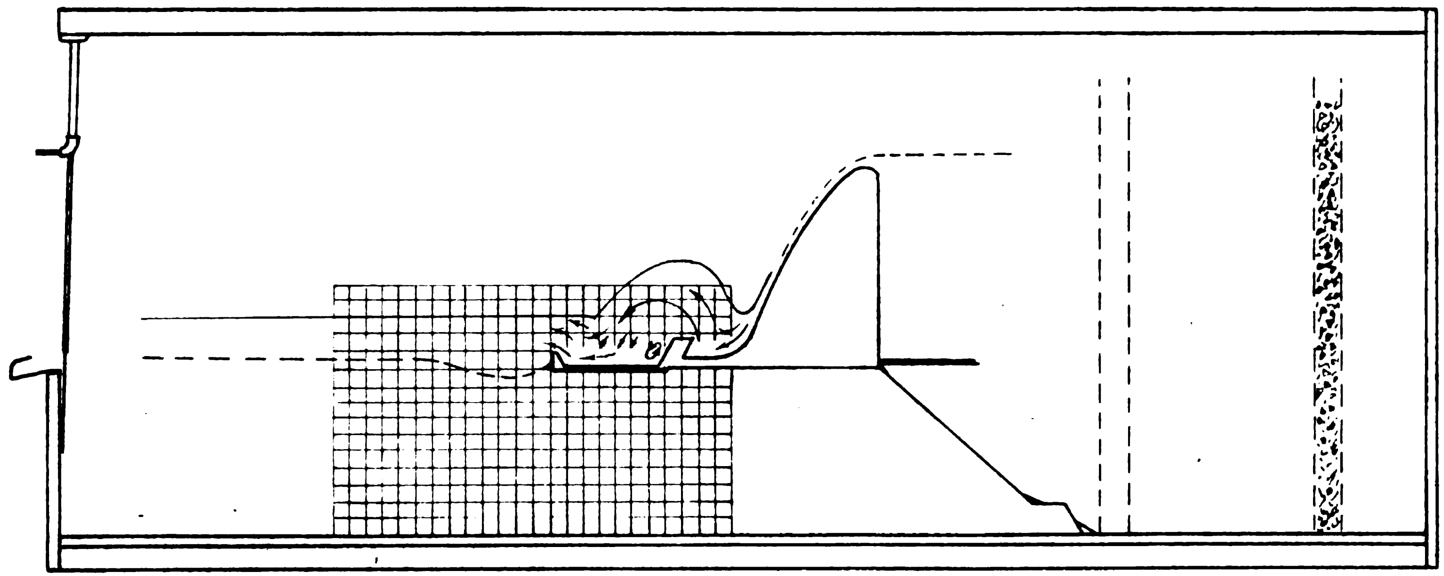


PLATE NO. 27

Quantity of Water in C.F.S. .178

Depth for Hydraulic Jump

This shows the most successful type of stilling device, a stilling dam inclined sixty degrees toward the main dam with a pool directly below it. Here it shows the effect during a small flow with ordinary depth of tail-water.

Stilling dam and pool same as above during a large flow with ordinary depth of tail-water ing pool. When the water leaves the stilling pool it is fairly quiet. Another thing of importance is the way the end of the stilling pool is constructed. It slants up at an angle of sixty degrees with the horizontal and tends to hold the water back. The water instead of shooting straight out in to the tail-water, is directed upward under it. During small and moderate flows, the water comes up under the tail-water through out the length of the stilling pool. There is still very little erosion. Although the water shoots out of the stilling pool at a higher velocity, being deflected up under the tail-water as it is, it has no chance to disturb the material below. Plate number twenty-seven shows a very large flow. Beyond this the water falls partly outside of the stilling pool after leaving the stilling dam, which causes a decided increase in the erosion. However, in plate twenty-seven the head on the dam was .102 feet and the dam is one foot high. This would correspond to a head of 10.2 feet on a dam 100 feet high, which is a very high head.

In order to determine the true merit of the foregoing type of stilling dam and pool, it is necessary to compare its operation with that of a plain apron extending out the same length and with a slight incline on the end of it.

An apron of this shape was designed and fastened to the toe of the dam. A small flow of water was allowed to run over the dam for some time. As long as the depth of the tail-water was high there was very little erosion. However the depth at which the tail-water had to be maintained was prohibitive. During even very small flows the loss of head was about one sixth the total head from the top of the dam. Plate number twenty-eight shows the condition during a small flow.

As the head is increased, the depth of the tail-water must also be increased in order to prevent erosion at all heads an artificial means of maintaining the depth of the tail-water must be employed that will prevent erosion at the highest head expected. In other words a down-stream weir must be constructed or the dam must be built so that the water will be discharged in to the proper depth of tail-water that will prevent erosion at the largest expected flow. Either way would increase the cost of construction.

For each successive flow the depth of tail-water required to prevent erosion is equal to the depth of water required to cause the hydraulic jump to form on the apron. As the head on the dam increases the required depth of tail-water increases. Plate mumber twenty-nine shows the action during a large flow with the depth of the tail-water adjusted so that the hydraulic jump will just form on the apron. This depth is 3.3 inches which is over one fourth the height of the dam. This means a large loss of head and expensive construction.

Unless some means is provided for assuring that the depth of tail-water is going to be enough to cause the hydraulic jump to form on the apron, there will at some time exist a

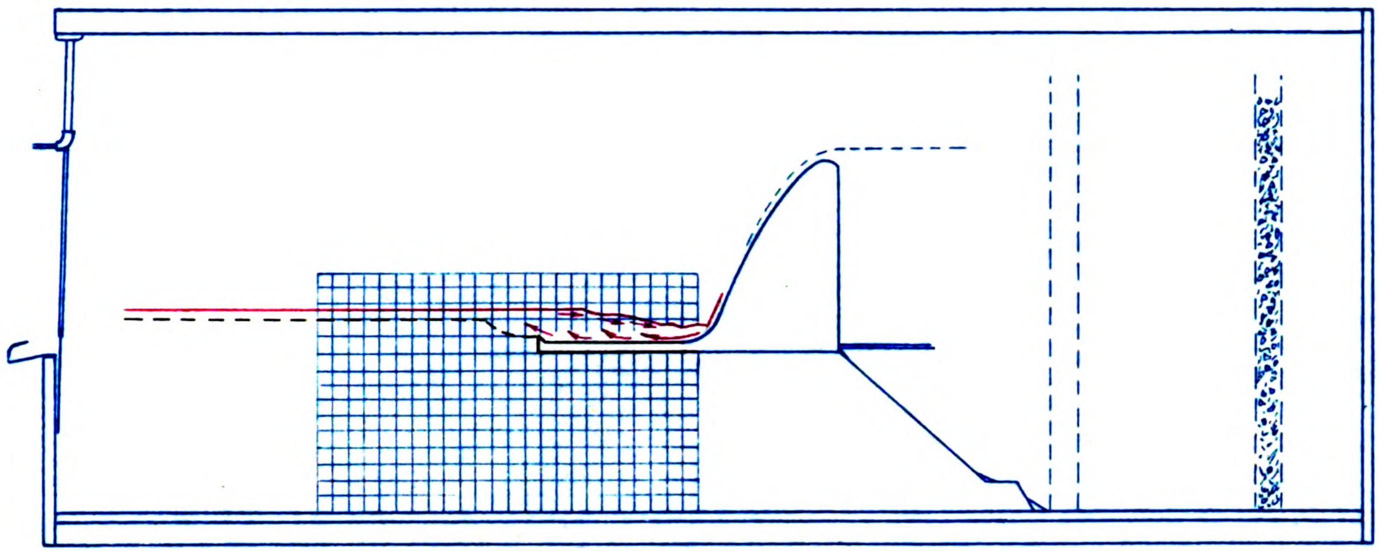


PLATE NO. 28

Quantity of Water in C.F.S. .046

Depth for Hydraulic Jump

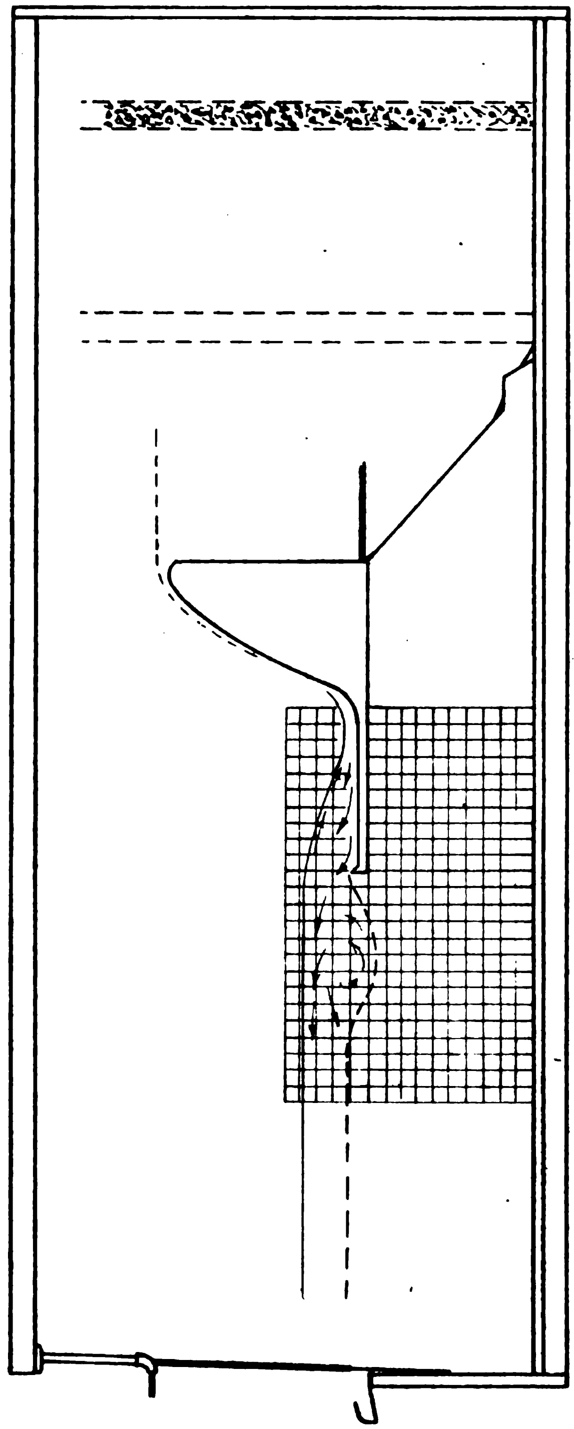
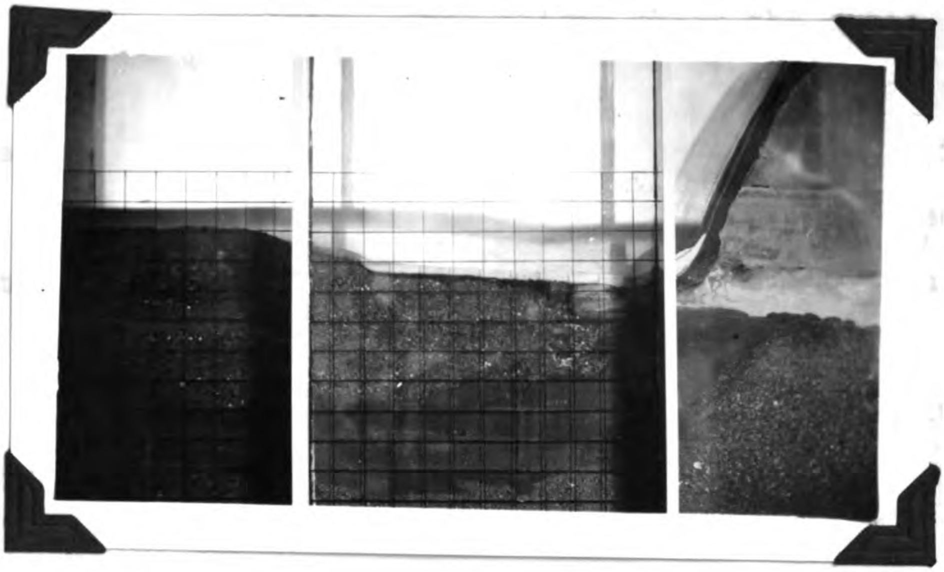


PLATE NO. 29

Quantity of Water in C.F.S. .194

Depth for Hydraulic Jump



This shows a plain apron nine inches long during a small flow with high tail-water.

Apron same as above during a large flow with high tail-water condition as shown in plate number thirty where the water continues along the apron in a sheet of swift unbroken water and then shoots out in to the tail-water. The energy that is contained in the water at the foot of the dam is still present in the water as it leaves the apron, except for that which is destroyed by friction.

At each increase in head the tail-water was maintained at a depth just below that required for the hydraulic jump to form on the apron, and at each increase in head there was a corresponding increase in the erosion. After the head had increased up to a certain point the erosion became more constant in depth and occurred farther from the edge of the apron. Also, due to the currents of water flowing back along the bottom, material was deposited under the edge of the apron where it had been eroded during the low flow.

After the conditions had become constant at a large flow, the head was decreased in steps. This caused the erosion to occur closer to the apron. The smaller the flow became the more material was carried away from the toe of the dam where it had been deposited during the high flow. The hole that was formed during the high flow was partially filled in by this material. This accounts for the decreased depth of the erosion. Plate number thirty-one shows a small flow succeeding a large flow.

With a very small flow and low tail-water, the material is eroded from under the apron. This shows that under all con-

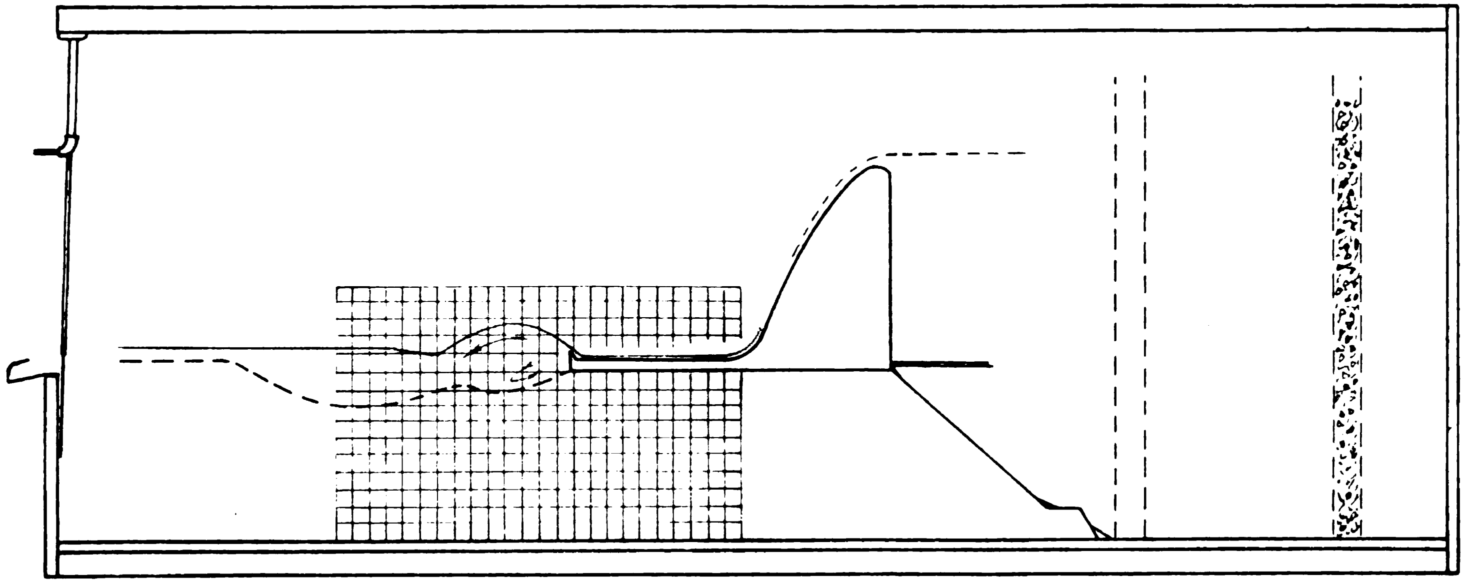


PLATE NO. 30

Quantity of Water in C.F.S. . .060

Depth for Hydraulic Jump

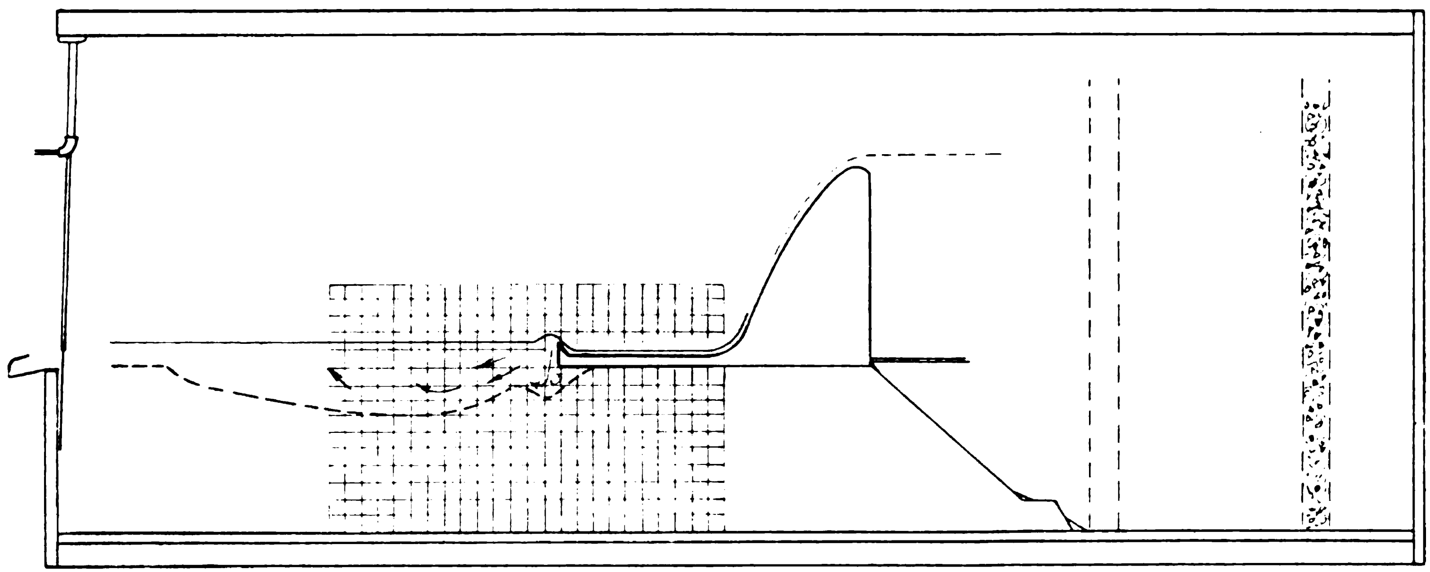
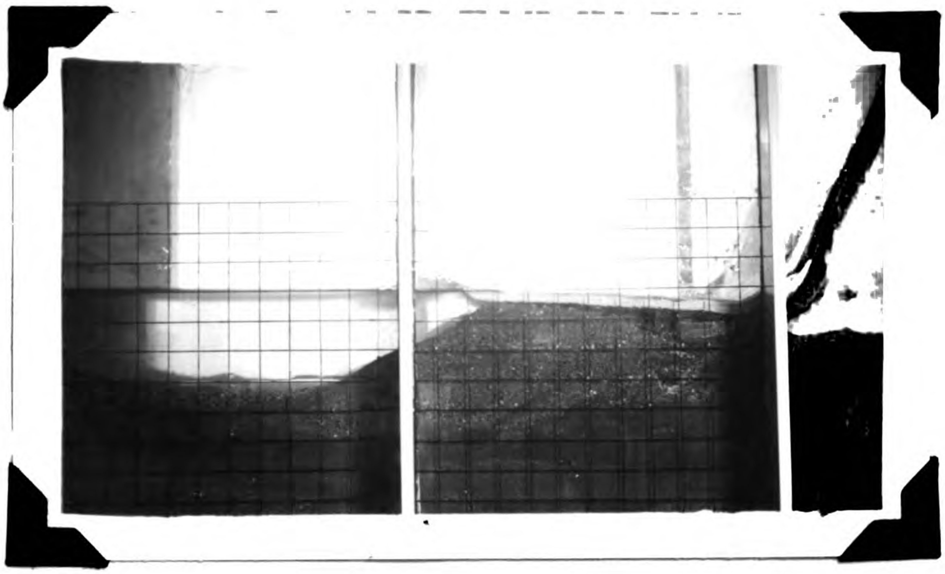


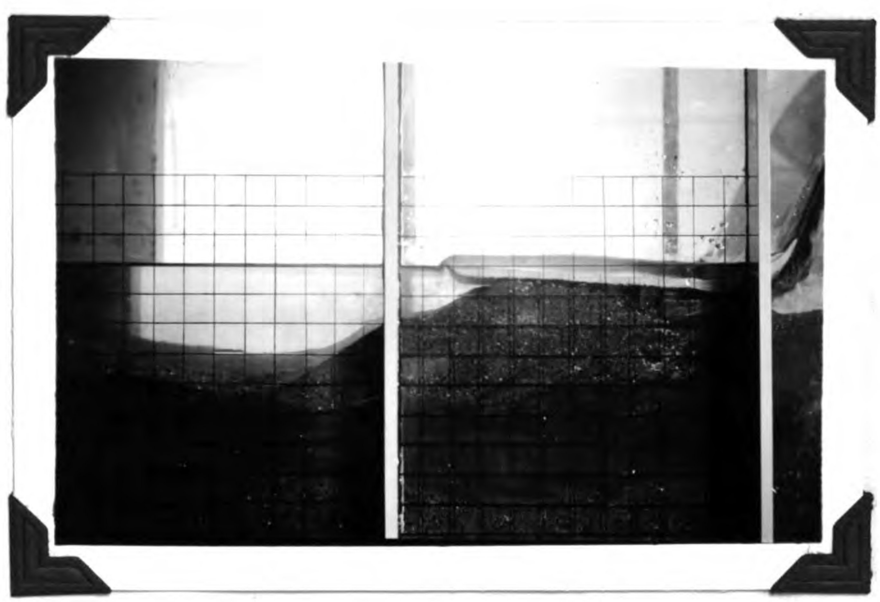
PLATE NO. 31

Ouantity of Water in C.F.S. .013

Depth for Hydraulic Jump



This shows the erosion due to a high head with the apron nine inches long and the tail-water too low.



This shows a small flow following a large flow with the apron the same as above and the tail-water too low.

ditions and with all stilling devices the tail-water must be high enough so that during small flows the water from the apron discharges below the surface. If the water during a small flow is allowed to drop in to the tail-water, erosion will always occur under the apron.

The results of these tests show that the stilling device with the stilling dam inclined thirty degrees toward the main dam and the stilling pool below it, is superior to the plain apron of the same length.

Conclusion

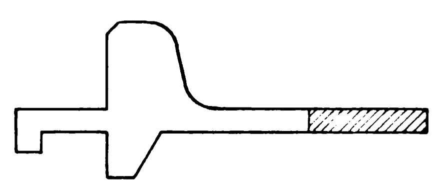
The conclusions that may be drawn from the foregoing experiments are, first, the depth of erosion for any given energy absorber depends upon the head of water going over the dam, the depth of the tail-water, and the time. The depth of the erosion increases as the head increases, and decreases as the depth of the tail-water increases. The depth of erosion is also a function of the time; however the maximum depth is approached rapidly so that in a very short time any additional erosion takes place very slowly.

Second, the distance of the erosion from the end of the energy absorber is a function of the head on the dam. The greater the head the farther downstream will the erosion occur. When the head decreases and the depth of the tail-water also decreases, the erosion will go back under the apron or stilling device.

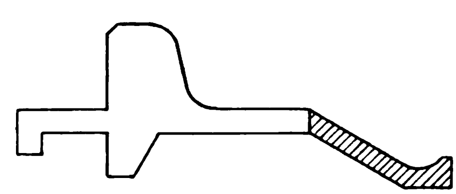
Third, the amount of erosion depends upon the depth of tail-water, the head on the dam, and the time. The greater the head on the dam the greater the amount of erosion, and the greater the depth of tail-water the less the amount of erosion. Over a long period of time the water going over a dam has a tendency to keep moving material downstream away from the dam, which makes time a factor in the amount of erosion.

Regarding the design of stilling dams, stilling pools,

and all other types of energy absorbers, two things must be kept in mind. First, as much of the energy of the water as possible must be absorbed by the stilling device. Second, care must be taken as to how the water joins the tail-water. If it strikes straight down there will still be erosion. An example of this was the Hamilton Dam at Hamilton Ohio. At first the dam had a plain apron with a flexible mat attached to the end of it. There was still erosion at the end of the apron. The flexible mat was removed and a depressed apron was put in its place, as a result the erosion was eliminated.



Before changing the apron

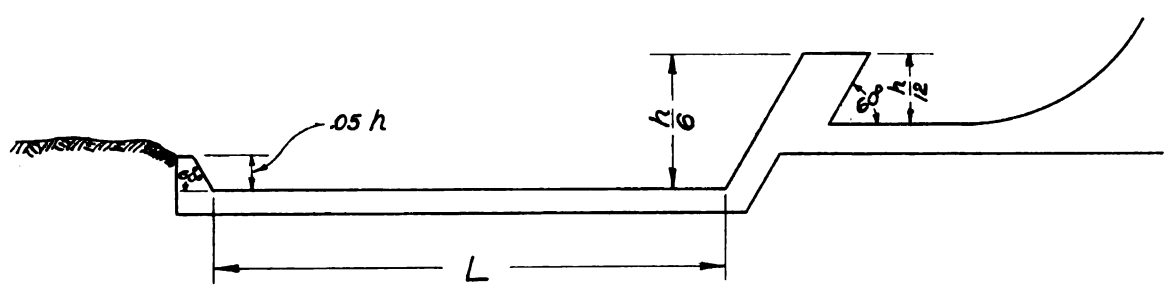


After changing the apron

It has been general practice to allow water coming over a dam to fall in to a stilling pool, or to strike against a stilling dam. In these experiments it was found that a stilling pool did not sufficiently absorb the energy of the water.

And a stilling dam caused the water to strike the tail-water at undesirable angles thus causing erosion. Unless the stilling dam was placed out far enough which then had the effect of a long stilling pool. By experimentation it was found that by placing a stilling dam inclined thirty degrees toward the main dam, and placing a stilling pool directly below it the most successful operation could be secured. A great deal of the energy of the water at the toe of the dam was absorbed by the stilling dam. The water after leaving the stilling dam was thrown in to the air in a spray, to be distributed over the pool of water directly below it upon falling. With a device like this the energy of the water is not only absorbed by the stilling dam but the remaining energy is distributed over the comparatively large area of water in the pool.

Below is a sketch of the proposed type of stilling device.



h = Height of dam

H = Head of water on the dam

Proposed relation of L

$$L = h\left[-.073 + 2.15\frac{H}{h} + 17\left(\frac{H}{h}\right)^2\right]$$

Following is the data upon which the foregoing empirical formula was based. On the next sheets may be found the computations.

Distance of stilling dam from toe	3"
Height of stilling dam	1"
Depth of pool below top of stilling dam	3"

Hook Guage Reading	Dist. out Water Falls
3.040	.0416
3.057	.1041
3.064	.1250
3.082	.2500
3.095	.3335
3.107	.3420
3.124	.4250
3.137	.5160
3.142	.6250
3.151	.6660
3.180	.8330

Data was taken with the idea of evolving a law for the design of plain rectangular stilling dams. However it was found that the results were so inconsistant that no reliable formula could be derived from them. Slight variations in the depth of the tail-water threw the results way off. The erosion was so uncertain in nature that no comparison could be made between one test and another. About the most that can be said of the rectangular stilling dam is that it must be placed at a distance from the toe of the dam equal to three fourths the height of the dam for successful operation. The height of the stilling dam should be .105 times the height of the dam.

x	y	Δx	Δy	$\frac{\Delta y}{\Delta x}$	y'	$2cx$	$b = y' - 2cx$	$2.14x$	$17x^2$	$a = y - 2.14x - 17x^2$
.04	.042				3.45	1.36	2.09	.0856	.0272	−.071
		.02	.077	3.85						
.06	.119				4.20	2.04	2.16	.1284	.0612	−.076
		.02	.091	4.55						
.08	.210				4.85	2.72	2.13	.1712	.1088	−.070
		.02	.103	5.15						
.10	.313				5.56	3.40	2.16	.2140	.1700	−.071
		.02	.120	6.00						
.12	.433				6.25	4.08	2.17	.2568	.2450	−.069
		.02	.129	6.45						
.14	.562				6.64	4.76	1.88	.3000	.3330	−.071
		.02	.138	6.90						
.16	.700				7.25	5.44	1.81	.3421	.4350	−.077
		.02	.155	7.75						
.18	.855				8.25	6.12	2.13	.3850	.5510	−.081

average for $b = 2.14$

average for $a = -.07325$

$$y = a + bx + cx^2$$

$$y' = b + 2cx$$

$$y' - 2cx = b$$

$$\text{Slope} = 2c = \frac{8.25 - 2.125}{.18} = 34.0$$

$$c = 17$$

$$b = 2.14$$

$$a = -.073$$

H = Head of water on dam in practice

h = Height of dam in practice

L = Length of apron in practice

Model dam is 1′ high

$y = -.073 + 2.15x + 17x^2$

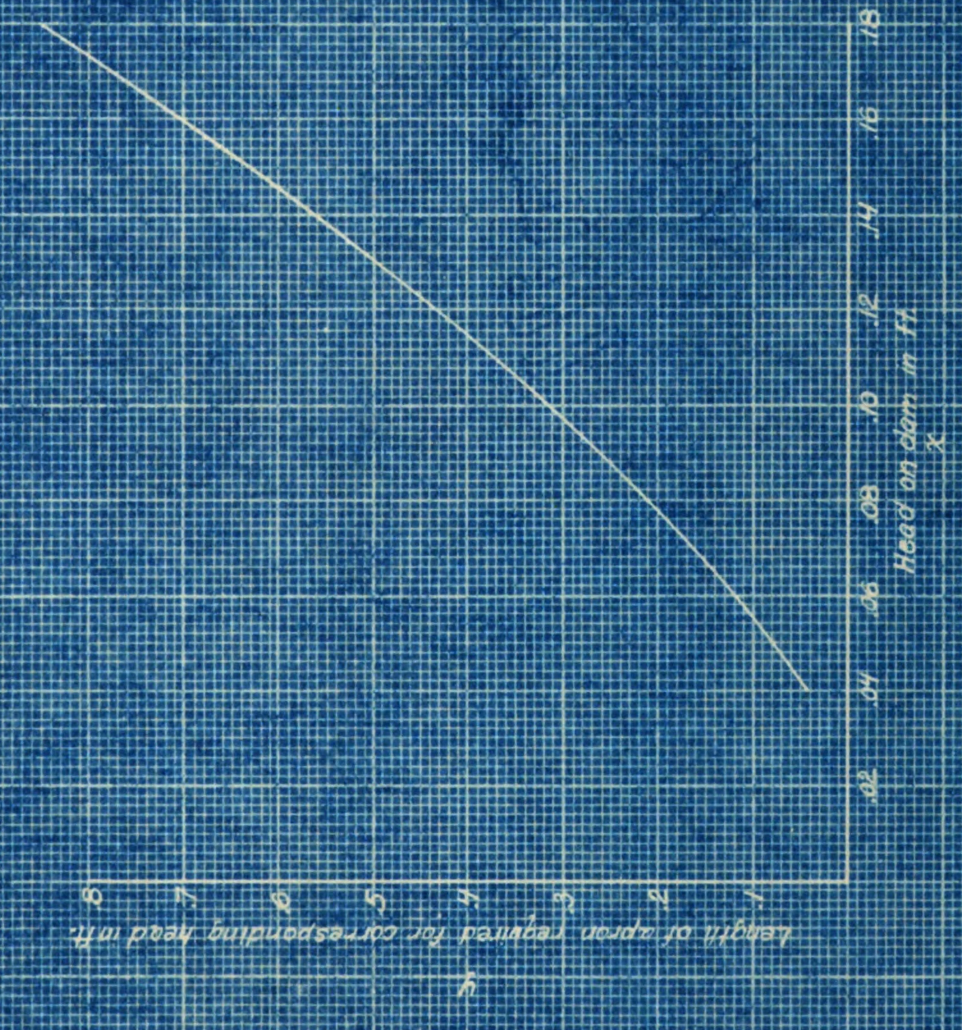
x = Head on the dam (model)

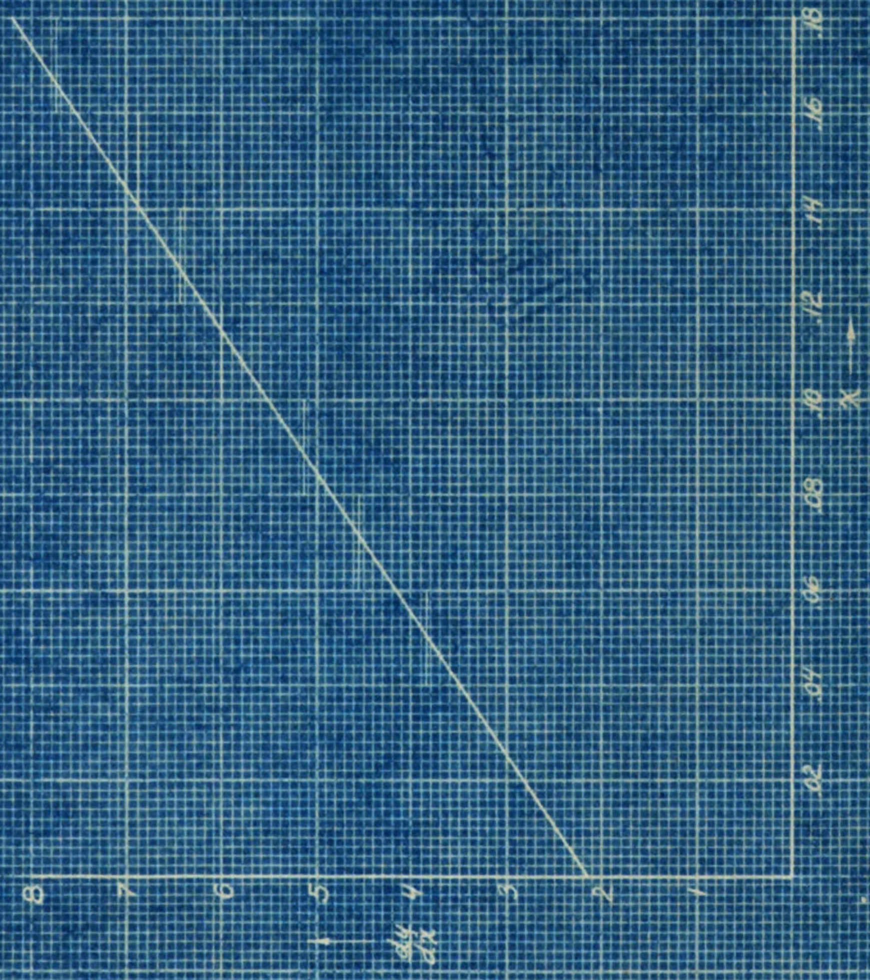
y = Length of apron (model)

$x = \frac{H}{h}$ $\quad$ $y = \frac{L}{h}$

$$\frac{L}{h} = \left[-.073 + 2.15\frac{H}{h} + 17\left(\frac{H}{h}\right)^2\right]$$

$$L = h\left[-.073 + 2.15\frac{H}{h} + 17\left(\frac{H}{h}\right)^2\right]$$


.02 .04 .06 .08 .10 .12 .14 .16 .18
Head on dam in ft.
x
1 2 3 4 5 6 7 8
Length of apron required for corresponding head in ft.
y


.02
.04
.06
.08
.10
.12
.14
.16
.18
x
1
2
3
4
5
6
7
8
dy/dx