VELOCITY, SCOUR AND PRESSURE MEASUREMENTS FROM THREE MODELS OF THE SAME STRUCTURE

by

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SUMMARY

This paper reports the results of a study made to compare the velocities and pressures at certain points in three models of the flood spillway and energy dissipator for a large dam together with the scour pattern developed in the riverbed downstream from the spillway. The models were of the same structure and were built on scale ratios of 1:15, 1:40 and 1:120. In general, comparisons of the data derived from the three models are in very good agreement. The results of the scour tests show that wall effects in models of narrow sections of structures may influence the scour pattern.

INTRODUCTION

The hydraulic laboratory studies discussed in this paper were made several years ago. However, the results obtained were not summarized or reported previously. Subject A for discussion at the Seventh Congress suggested that the material be assembled and examined. The principles involved are of a basic nature and the results remain of value to hydraulic research engineers. Therefore, the findings are reported at this time.

The hydraulics of one particular feature of a major structure can be solved readily on a model constructed on a selected scale ratio. A larger or smaller model may be advisable for the study of the hydraulics of other features. Hence, in the solution of hydraulic design problems in a large spillway, it may be desirable to employ models of more than one scale ratio.

Hydraulic models were used extensively by the Bureau of Reclamation to assist in the design of the flood spillway for Grand Coulee Dam, Figure 1. Each model was constructed for a definite purpose. After certain features had been studied on smaller models, a model representing approximately one gate length of the spillway was built on a scale ratio of 1:40 primarily for study of the energy dissipator. A similar sectional model was later constructed on a scale ratio of 1:15. Another model, of the entire spillway, other parts of the dam, the powerhouses and a reach of the downstream river was constructed on a scale ratio of 1:120 to study the general hydraulics of the structure and adjacent river channel.

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After the immediate design problems were met, minor revisions in the three models permitted studies of velocities on the face of the dam in the spillway section and in the energy dissipator; pressures on the energy dissipator; and scour patterns in the riverbed downstream from the spillway. A comparison of the results from each model was thus permissible and an opportunity was offered to evaluate the manner in which each model might predict the action in its prototype.

THE MODELS

The 1:40 scale ratio model was built in the hydraulic laboratory of the Bureau of Reclamation at Fort Collins, Colorado. The model was initially used to study a dentated lip proposed for installation in the energy dissipator of the flood spillway of the dam. Certain difficulties were encountered in the pressure studies and the 1:15 scale ratio model was built. A model of this size could not be constructed and operated in the Fort Collins laboratory because the facilities there were not adequate. For this reason the model was built at the hydraulic laboratory of the Bureau of Reclamation at Montrose, Colorado. The two laboratories had considerable geographic separation. The 1:120 scale ratio model was built in the Fort Collins laboratory.

The hydraulic laboratories of the Bureau of Reclamation at Fort Collins and Montrose, Colorado, are now closed. The functions performed at these installations are now carried on at the Bureau's laboratories in Denver.

After completion of the studies for which each model was constructed, revisions were made to bring them into as close agreement as possible before the comparative studies were initiated. The essential dimensions of the models as revised are shown in Figure 2.

The models were initially fitted with gates closely simulating the drum gates provided for control of the water surface above the fixed crest. These gates are shaped in such a manner that when down they form a part of the overflow crest of the spillway. For all comparative tests, except the scour tests, the gates, on all three models, were sealed in the down position. Thus the flow, in effect, was over a rounded crest as shown in the drawing. The crest shapes on the three models were not identical in all details but major dimensions did conform. Discharges were carefully measured by laboratory methods. Observations of the water surface upstream from the crest showed very close agreement for all three models and confirmed the similarity of the crests.

The width of the 1:15 model was such that it represented one full gate length of the spillway as finally designed. The 1:40 model was built at an earlier stage of design development. The width of this model represented one gate 105 feet long instead of the 135-foot length of the final gates. The 1:120 model contained all 11 of the 135-foot-long gates separated by piers 15 feet thick. Revisions to this model included

training walls constructed on the spillway face, through the energy dissipator and extending downstream to provide one gate length and conform to the dimensions of the other two models.

A half pier was included at each end of the crest section of all models. Thus, the length of prototype spillway represented in each model was as shown in Figure 2.

The face of the spillway and energy dissipator was formed of galvanized sheet metal in the 1:40 and 1:120 scale models. All joints were carefully smoothed to present a continuous surface to the flow. The face of the spillway and energy dissipator was constructed of wooden planks in the 1:15 scale model. All joints were filled and the entire surface was planed, sanded, and treated with oil. The surfaces were maintained in excellent shape during the time the comparative studies were made.

The cross-sectional areas of the approach channels for the three models were not correctly proportioned as may be seen from the figure. Therefore, the velocity of approach to the crest section of the spillway was not in identical relationship for each model.

For purposes of comparison, all data derived from the models were transferred to prototype values. Hence, reference will be made to the prototype values throughout the paper and all plots and drawings bear prototype quantities.

THE TESTS

The studies were planned to provide data which would be comparable. This prior planning for the tests accomplished a great deal toward insuring that equipment and techniques employed on the three models were as nearly identical as was possible to attain. Geographical separation of the models, the fact that the studies were not made simultaneously, and the necessity for having different personnel conduct the tests precluded identical procedures. However, only minor deviations from the basic proposals previously drawn are known to exist.

The prototype flood spillway was designed to pass a maximum discharge of 1,000,000 second-feet. This amounts to 673.4 second-feet per foot length of free spillway crest. The model flows were correctly proportioned for the equivalent length of free crest represented in each model and were accurately measured by accepted laboratory techniques. The flows used throughout the series of tests represented floods of 250,000, 500,000, 750,000, and 1,000,000 second-feet or 25, 50, 75, and 100 percent of the maximum design discharge of the spillway.

The use of different methods for extending the tail water rating curve at the dam site resulted in two slightly different curves being used for the comparative tests. The curve used for the 1:15 scale

model was in agreement with the one used for the 1:40 and 1:120 scale models for prototype discharges up to and including 500,000 second-feet. However, the former was 1.25 feet above the latter at 750,000 second-feet and 2.50 feet above at maximum discharge of 1,000,000 second-feet. The difference between the curves in the upper ranges of discharges is quite small percentage wise and thus should not be appreciably reflected in the results. The disparity was not noted until after the tests were completed.

Accepted hydraulic laboratory techniques and equipment were used throughout the series of tests. Usual transfer equations were employed to convert model observations to prototype values.

Testing procedures for each of the types of studies conducted are explained more fully under the subject headings.

Although a rather extensive program was initially proposed, operational difficulties and time limits precluded completion of some parts of the series of studies as will be noted later.

VELOCITY OBSERVATIONS

General

The test program, as originally proposed, contemplated a study of the magnitude and distribution in depth of velocities in all three models. These studies were to be made on the face of the spillway and at four stations in the energy dissipator. Flows represented one-fourth, one-half, three-fourths, and maximum design discharge. No studies of the velocity distribution across the sections were proposed because the presence of the side walls in the sectional models created a condition not found in the prototype.

The velocity traverses were made on the longitudinal center line of the models to avoid insofar as was possible the effects of the side walls on the flow. The velocity was observed at points distributed throughout the depth of flow from near the bottom to near the water surface.

In general, only those data which permit comparison of velocities in all three models are given in this paper. Considerable additional data were taken particularly on the 1:15 scale model.

Periodic observations of the level of the water surface upstream from the crest were made in all three models to determine that the head on the crest remained comparable.

Velocities on the Face of the Dam

Velocity traverses of the flow on the face of the dam at 25 and 75 percent of the design maximum discharge were made in each of the

three models at an elevation corresponding to prototype elevation 950.0. Observations at discharges representing 25 and 100 percent design maximum discharge were only partially completed on all of the models and the results are therefore not included here. The tail water in the models was lowered to insure that no backwater effects were present.

All velocity measurements were made with Pitot tubes. The same instrument was used for observations on the 1:40 and 1:15 scale models. A Pitot tube of very similar construction but of smaller dimensions was used on the 1:120 scale model. Neither of these tubes employed a static leg. The water surface was carefully measured for each observation and the static pressure was calculated. [1]

The results have been transferred to prototype values and are shown in Figure 3. The theoretical average velocity line shown with the observed curves is the velocity as calculated at the section neglecting friction on the face of the dam. The average water surface above the spillway was used in the calculations.

The difficulty of accurately observing the water surface on the slope probably influenced the results to a greater extent than any other known factor. The greater observed depth in the 1:15 scale model was probably due to the higher degree of surface turbulence. There may have been a slight bulking of the flow due to air entrainment as air was known to be present in the flow. The velocity of approach to the crest varied slightly in the three models. However, corrections for this difference in velocity for selected points showed only an insignificant change. Hence, the observed velocities are shown.

The roughness of the surfaces along the wetted perimeters of the three models was not geometrically similar to the roughness which might be expected in the prototype. This dissimilitude was probably more pronounced in the 1:120 model although care was taken to obtain a very smooth surface.

The results indicate that velocities obtained from the three scale ratio models when transferred to prototype values show very close agreement. It is not apparent from the studies that a limiting factor on the size of model was reached.

Velocities in the Energy Dissipator

The dissipation of energy in the scour protection facility as designed for the toe of the spillway section of the dam is partially dependent upon the thickening of the jet of water as it passes through the bucket and partially dependent upon the formation of a large roller

[1] Harold Lauffer, Druck, Energie und Fliesszustand in Gerinnen mit grossem Gefalle (Pressure, Energy and the Resistance to Flow in Channels with High Gradients) Wasserkraft und Wasserwirtschaft, Vol 30, No. 7, January 1935.

within the bucket. To supplement other observations of this energy dissipation a very complete study of velocity distribution in the energy dissipator was made on the 1:40 scale model. Selected sections were also studied in the 1:15 and 1:120 scale ratio models to obtain comparisons.

Pitot tube traverses were made from the bucket to the water surface at 4 sections on the center line of each of the 3 models, with discharges representing one-half, three-fourths, and maximum design capacity of the spillway. The tail water was controlled to conform to the predicted backwater curve downstream from the dam.

The results of the velocity observations transferred to prototype values are shown in Figures 4, 5, and 6. It will be noted from the plots that there is a difference in the distance traversed. This was a result of difficulty experienced in locating exactly the neutral position of the roller. The axis of the roller did not remain in a fixed position but moved up and downstream and vertically. This movement was spasmodic and occurred with such rapidity that readings could not be obtained from the Pitot tubes being used. The area affected was relatively large. In the 1:120 model the change of position of the axis of the roller was so rapid and the quantities being measured were so small that it was not possible to secure observations in a considerable area of the flow. For this reason, the curves from the small model do not extend as far from the bucket as the curves from either of the two other models.

It may be observed from a comparison of the velocity curves that the velocities in the 1:120 scale model were higher in the lower portion of the traverse but decreased rapidly as the traverse continued upward. This indicates that possibly the energy dissipation was not effected as rapidly in this small model. The shape of the water surface profile above the bucket also showed less dip in the smaller model.

It is interesting to note from the water surface profiles, shown with the velocity curves, that the action in the energy dissipator was slightly different in each of the models. This offers some explanation of the differences in velocities. The tail water curve used for the 1:15 model was slightly higher for the larger flows than that used for the other two models. This difference has been explained previously.

Considerable quantities of air were carried by the water in the energy dissipator. This added to the difficulties of obtaining observations.

The results show that it was possible to obtain more complete velocity observations in the larger models. Therefore, it may be concluded that the size of the model is an important factor for consideration when a thorough investigation of energy dissipating devices is contemplated.

PRESSURES IN THE ENERGY DISSIPATOR

The Studies

Twenty-nine small piezometer openings were installed in the bottom of each of the energy dissipators of the 1:40 and 1:15 scale models to observe the pressures acting on the structure. These openings were located generally along the longitudinal center lines but some had slight offsets to right and left to avoid openings located closely downstream from each other. Each opening was connected to a gage glass for observing the piezometric pressures.

Because of the difficulty of installation and the small size, no piezometers were installed in the 1:120 scale model.

Pressure observations were made for flows representing one-fourth, one-half, three-fourths, and maximum design discharge for the spillway. The tail water was controlled at all times to the desired elevation.

The Results

The results of the studies, transferred to prototype values, are shown in Figure 7. The curves in this figure are in very close agreement. There is no apparent effect in the pressure measurements of the slightly higher tail water elevation in the 1:15 model. The pressure curves, when compared with water surface curves shown in Figures 4, 5, and 6, show close agreement.

Since both models were relatively large, there was no indication of size limitations for pressure studies.

SCOUR STUDIES

Assumptions and Bed Materials Used

The purpose of the scour studies was to compare the similitude of the scour of bed material downstream from the energy dissipator in the three models.

The riverbed at the dam site is composed of clay, sand and gravel. The material has definite cohesive qualities. There is some cementing of the sands and gravels. Therefore, no attempt was made to represent the field material in the models.

In models of spillways and outlet works, the riverbed is usually represented with a cohesionless material. If repeated runs do not result in a sorting effect and a change of gradation or grain size in the material in a model, the effectiveness, as an energy dissipator, of various structures tested may be compared on the basis of the scour pattern produced. It is not common practice to attempt

to determine in models of this type the exact depth and extent of scour which might be expected in the prototype.

The basic assumptions made in selecting materials for the three models were (1) that the gradation and size of the material used to simulate the stream bed should be such that amounts varying as the cube of the scale ratio would be moved by systems of dynamically similar forces; and (2) a force sufficient to move bed material in one model, when reproduced to scale in another model, should be sufficient to move the bed material in that model also. This action is assumed to prevail if the mean diameter of the grain size is made proportional to the scale ratio of the model, and cohesion within the material is considered to be nil.

This assumption was followed in selecting suitable materials for use in the beds of the three models. The 1:15 model necessitated the largest amount of bed material below the spillway. Therefore, this model was used as a standard from which to determine the particle size of the material for the other models. Material which was readily available in the quantity needed was slightly larger than was desirable but when represented to scale on the 1:120 model was considered suitable.

A sieve analysis of the materials used in each of the models is given in the following table:

Sieve size in inches	Percent passing--by weight			
		1:40 model		
	1:15 model	Before tests	After tests	1:120 model
0.525	100.0			
0.371	78.0			
0.263	33.4	100.0	100.0	
0.185	8.3	76.1	96.1	100
0.131	6.2	65.0	72.3	99.6
0.093	1.8	43.1	49.4	
0.065		8.9	26.7	
0.046			4.8	71.2
0.0328		3.0	2.0	
0.0232		1.7	0.8	11.4
0.0116		0.9		0.6
0.0058		0.7		0.3
0.0029		0.3		0.1

Testing Procedure

An inspection of the flood hydrographs of the Columbia River at the dam site showed that it would not be possible to operate the models in their correct time scale because of the time limitations involved. If the general trend of the river hydrographs were followed in the models, tests at the lower flows causing the least damage

to the riverbed would have required considerable time. For the upper range of flows the rate of increase in discharge in the models would have been extremely rapid.

A study of operating conditions in the three models indicated that a flow representing 50,000 second-feet in the prototype could be introduced slowly and maintained a sufficient length of time to properly adjust all gaging equipment without appreciable movement of the bed material. The total time to raise the discharge from the flow of 50,000 second-feet to maximum discharge was fixed at 40 minutes for the 1:15 model. When properly scaled this time was 24.5 minutes and 14.2 minutes in the 1:40 and 1:120 scale models. The time required to raise the discharge to any intermediate flow was directly proportional to this total time. The discharge was decreased in the same manner.

The water surface upstream from the spillway was controlled in the 1:40 and 1:120 scale models to a level corresponding to prototype elevation 1288 by means of the crest gate for all flows except maximum discharge. The reservoir rose to elevation 1290 in the 1:40 model and to 1291.5 in the 1:120 model for this flow with the gate completely lowered. The gate on the 1:15 model was rendered inoperable prior to the commencement of the comparative tests. Therefore, the water surface upstream from this model was uncontrolled for all flows. The result was a slightly lower velocity of flow entering the tail water for the 1:15 model. The resulting percentage difference was very small in relation to the actual velocity and was neglected in the calculations.

Profiles of the water surface along the longitudinal center line of the models were made concurrent with the scour tests.

The Results

The results of the comparative scour tests are shown in Figures 8, 9, 10, and 11. The longitudinal profiles were taken along the center line of the model. The four sections across the flume, made at each of the four discharges represented, show that the effects of the sides of the flume were much more pronounced in the small model than in the larger models. For this reason, profiles taken along the center line do not give a true picture of the scour. Calculations show that the total amount of material removed by scour was, in general, inversely proportional to the size of the model. However, at maximum discharge, Figure 11, the material was entirely removed from the sand bed in the 1:120 scale model except for a small amount near the lip of the bucket and another small volume near the outlet of the flume. Had the sand bed been deeper, possibly the total movement would have been much greater in this model.

It should be noted from Figures 5 and 6 that maximum velocities leaving the lip of the bucket in the 1:120 scale model were higher than in either of the other two models. At maximum discharge,

Figure 6, this difference was appreciable. Evidently the energy was not as effectively destroyed in this model and hence greater scour, especially at the maximum discharge, could be expected.

Some sorting of the materials in the 1:40 scale model during the scour tests is evident from the table giving sieve analyses. Although no analysis was made of the materials in the 1:15 and 1:120 scale models after the tests, it is possible that some change did occur which could influence the scour pattern.

The studies conducted on the models also included a number of observations which may be summarized here. Several tests of short duration, with selected flows, were made on all three models to ascertain if repeated flood flows of short duration would produce the equivalent scour of a single flood of duration equal to the sum of the short periods. It was determined that the resulting scour, for each discharge tested, was very similar. It was also demonstrated, with the materials used, that flows representing sustained flow in the prototype of approximately 1-1/2 hours duration produced scour patterns very similar to the patterns produced with much longer periods of operation. The minimum length of sustained flow to produce patterns identical to those produced by the longer runs was not determined. However, the riverbed, within the relatively short reach tested, was stabilized very rapidly for a constant sustained discharge.

The downstream riverbed represented in the 1:120 model was doubled in length. A series of runs made with this greater length produced a slight decrease in total scour for an equal period of time. However, the effects of the side walls were quite pronounced and the total scour apparently was not in true proportion.

Conclusions which may be drawn from the scour tests include the following: The basic assumptions made in regard to scale relationships of the mean grain size were not borne out by the observations. The data are not adequate to generalize the results or establish corrections, particularly in view of the side wall effects in the small model. The results of scour tests conducted on sectional models may be greatly influenced by the side wall effects. Therefore, the sectional width selected should be adequate to reduce these effects to a minimum or a larger model should be used. The runs need not be for prolonged periods to produce stabilized scour patterns. The minimum length of time, although not definitely determined, will depend on the size of the model and the size and type of materials utilized.

For the type of materials used and the scale of the mean grain size employed, the small model developed considerably more scour than the larger models. This is particularly true for the high flows. Just how much the flow pattern was disturbed by the side wall effects was not determined.

CONCLUSIONS

The series of studies was not as complete as was originally planned. Because time did not permit investigation of the causes of inconsistencies or extension of the investigations to determine exact limitations, only general conclusions may be drawn.

The results of the velocity studies made on the face of the spillway show very good agreement and no limitation regarding size of models is evident. The spread in observed depths of flow is in all probability due to the difficulty in determining the exact water surface because of turbulence and spray. Special equipment should be utilized in future studies of a similar nature to observe the exact depth of flow more closely.

The effect of the sides on the flow was evident in all three of the sectional models. These effects were more pronounced in the small model. Therefore, it may be concluded that the model was too small for the particular studies undertaken or the model width selected was not adequate. Plans for future studies of a similar nature should include an investigation of the permissible width which can be effectively utilized.

The action of the energy dissipator, including the scour patterns, in the 1:120 scale model varied from that evidenced in the two larger models, especially at the high discharges. Again this would indicate that the size of the model should have been increased for the studies undertaken.

Definite conclusions were not reached from the results of the scour studies as to whether or not the basic assumptions were in error. Side effects on the flow, with a subsequent influence on the scour pattern, and the possibility that some sorting of the bed materials occurred during the tests could have influenced the results.

If similar tests are to be undertaken in the future the results can be greatly enhanced if the models are not geographically separated. The same personnel should conduct the tests on all models. The equipment and techniques employed should be as nearly identical as is possible. Careful planning of the tests cannot be overemphasized.

FIGURE 1--GRAND COULEE DAM--FLOOD SPILLWAY OPERATING.

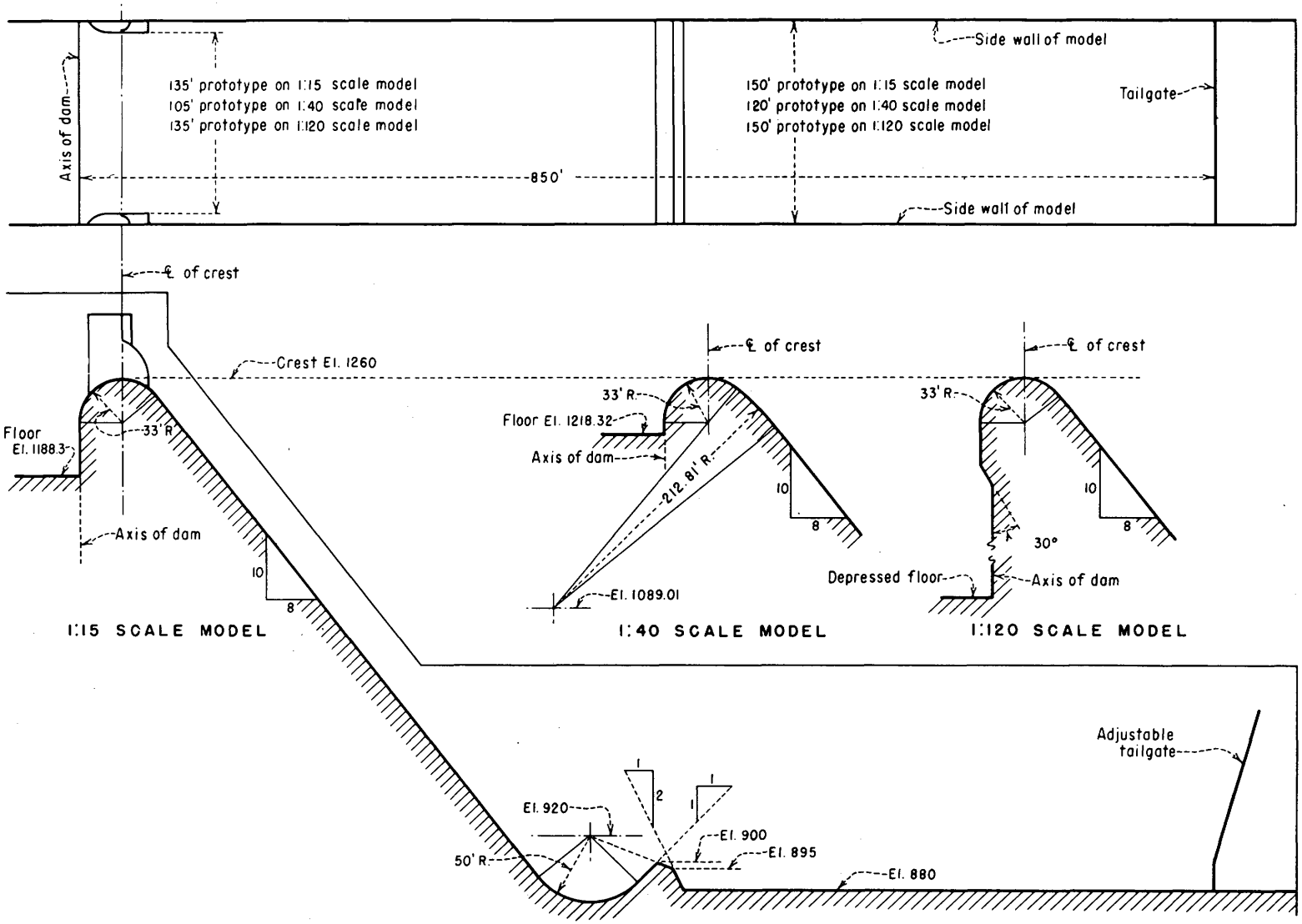
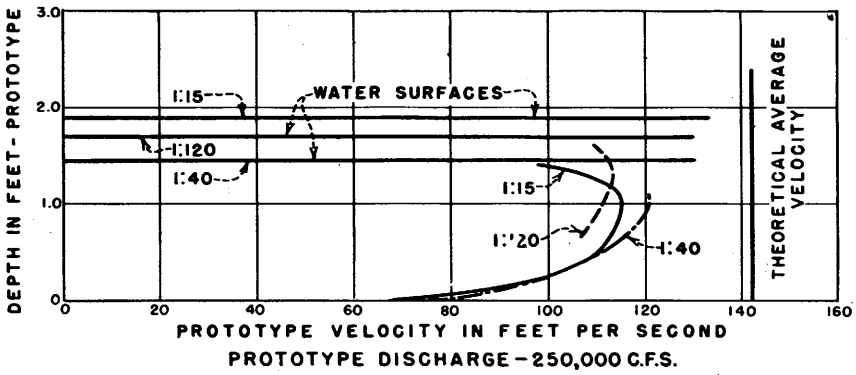
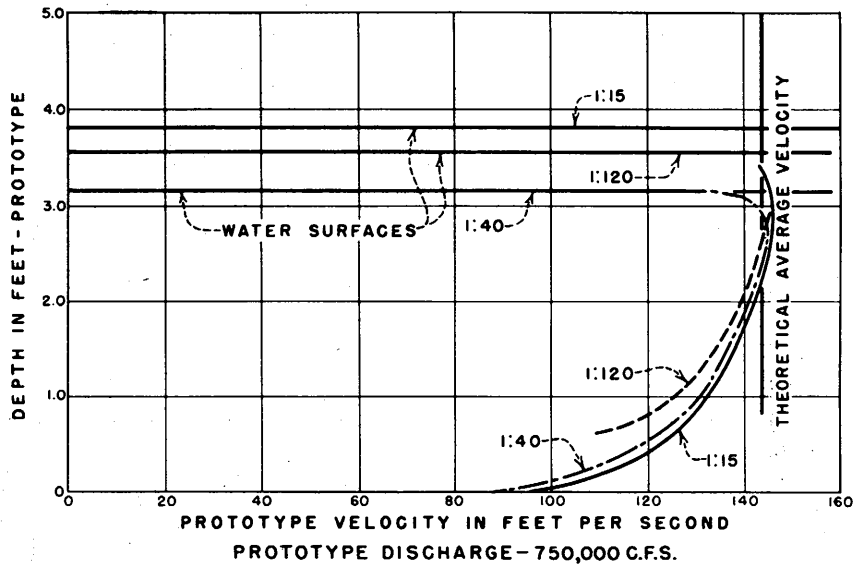
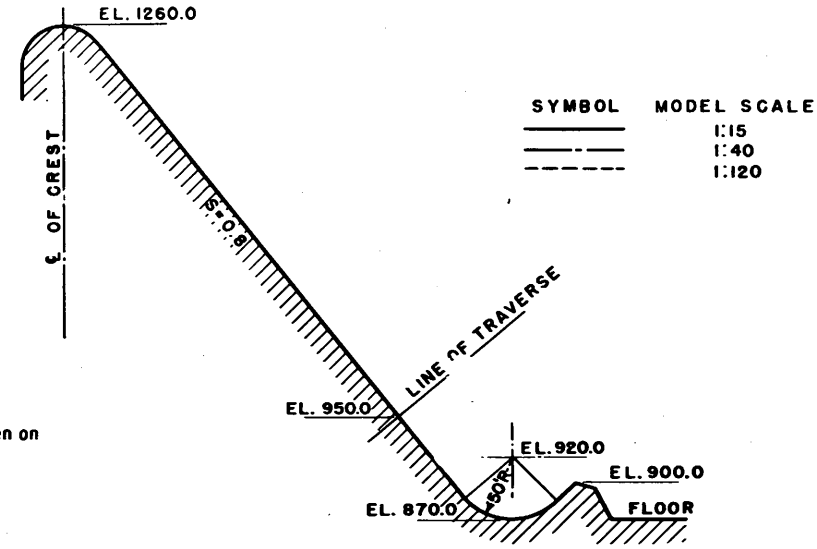


FIGURE 2 - THE THREE MODELS







NOTE
Sections were taken on ℄ of model

FIGURE 3
COMPARISON OF VELOCITIES ON FACE OF DAM

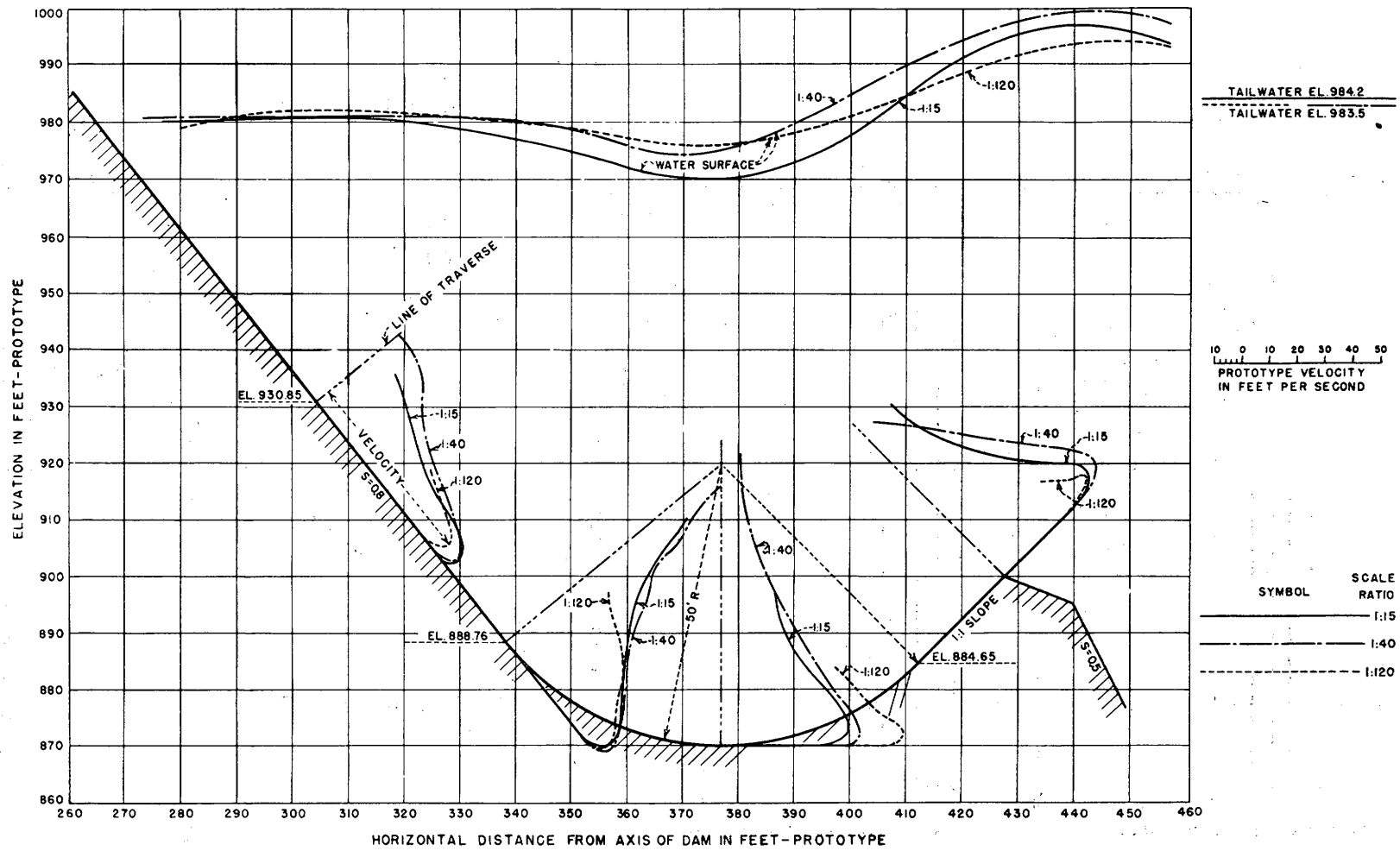


FIGURE 4 - ENERGY DISSIPATOR
VELOCITIES AND WATER SURFACES - PROTOTYPE DISCHARGE = 500,000 C.F.S.

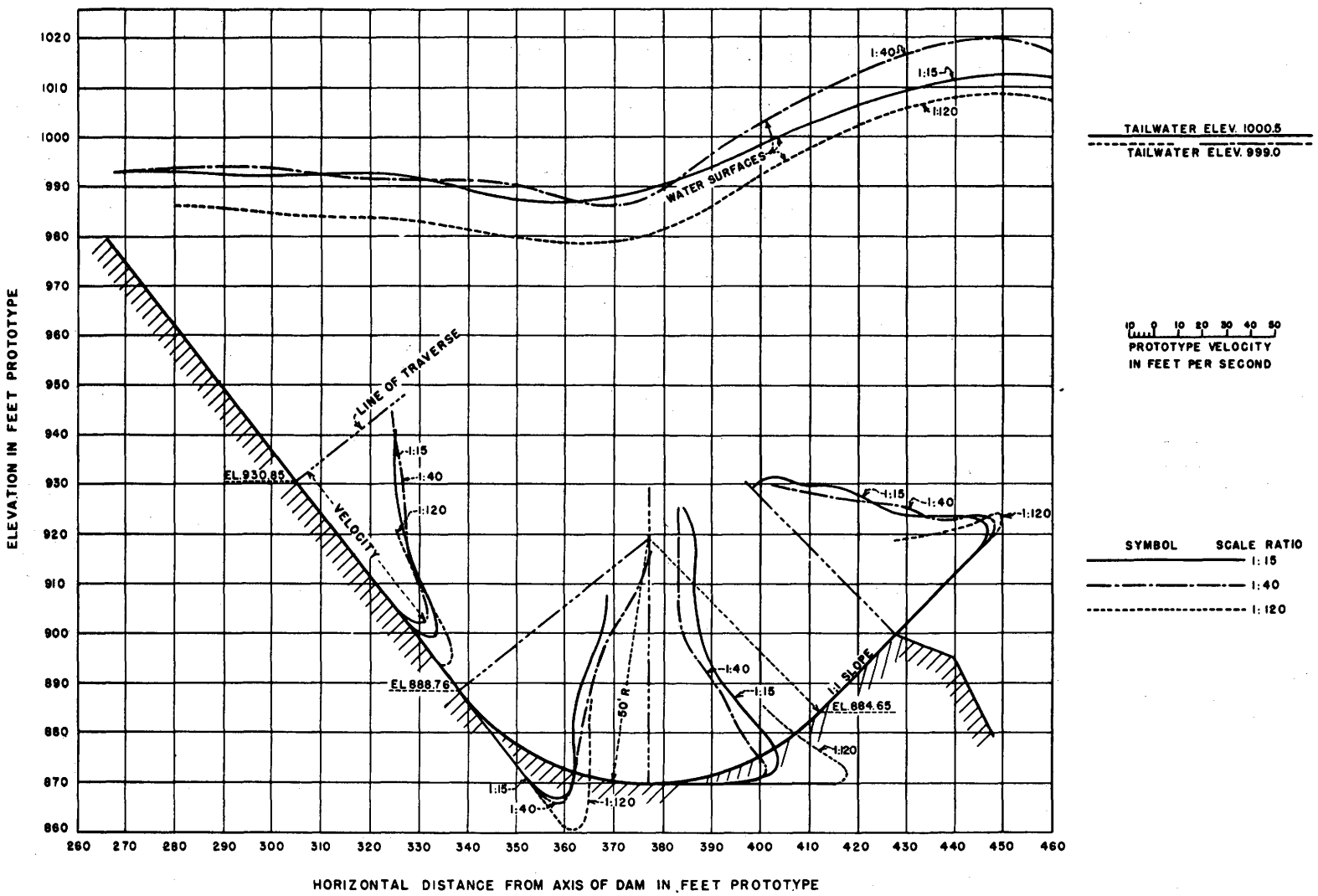


FIGURE 5 - ENERGY DISSIPATOR
VELOCITIES AND WATER SURFACES - PROTOTYPE DISCHARGE = 750,000 C.F.S.

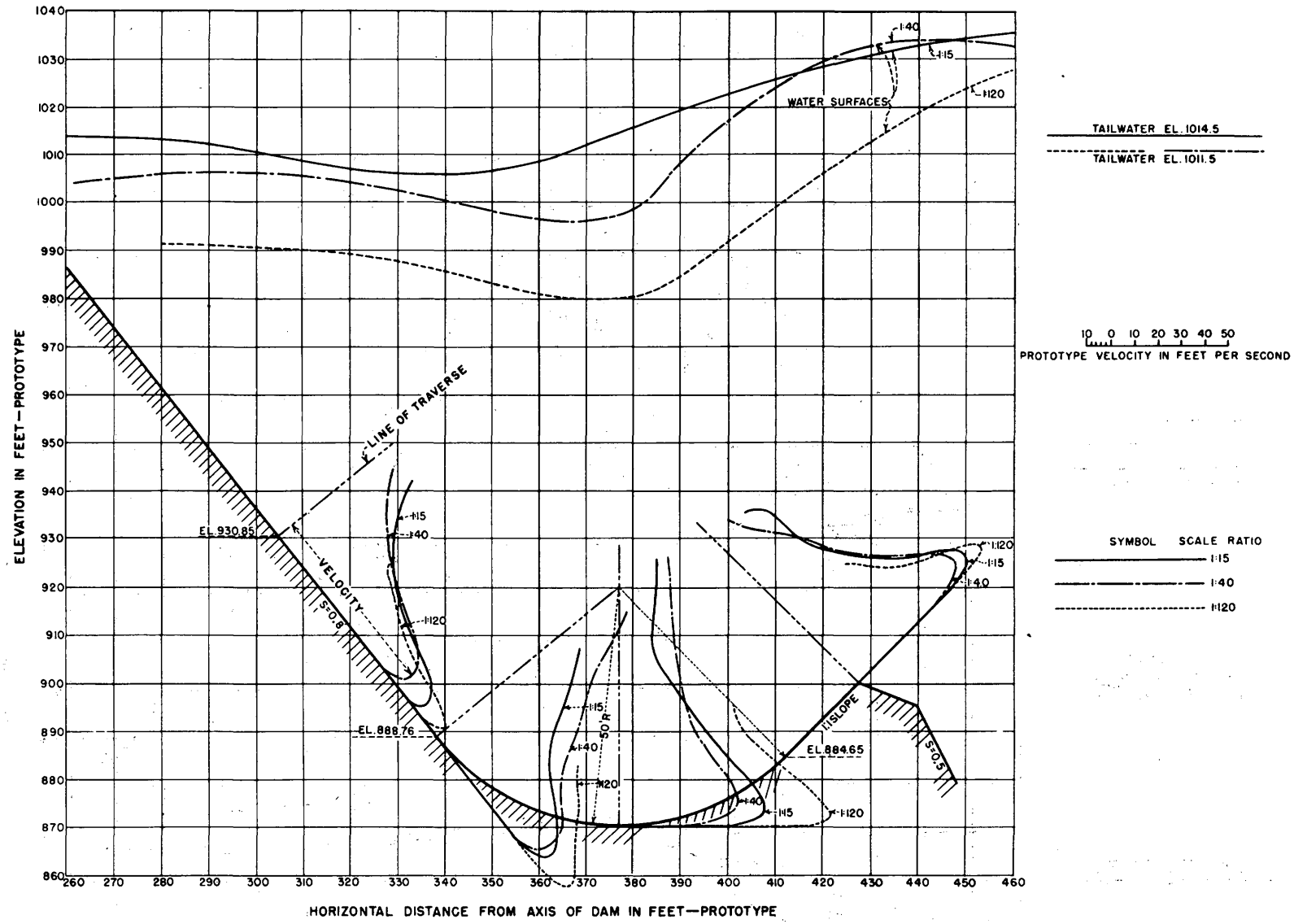


FIGURE 6 - ENERGY DISSIPATOR
VELOCITIES AND WATER SURFACES - PROTOTYPE DISCHARGE = 1,000,000 C.F.S.

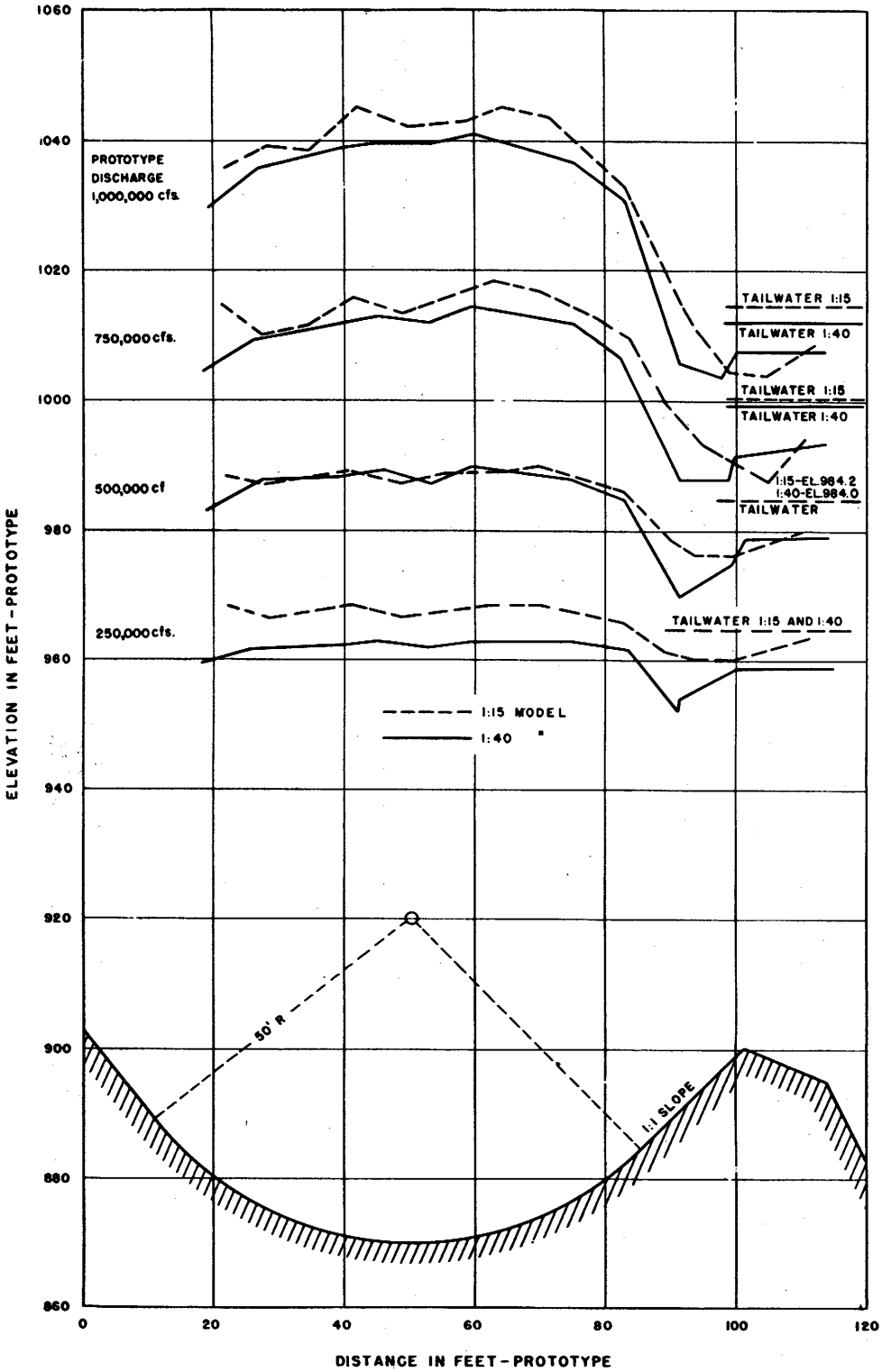
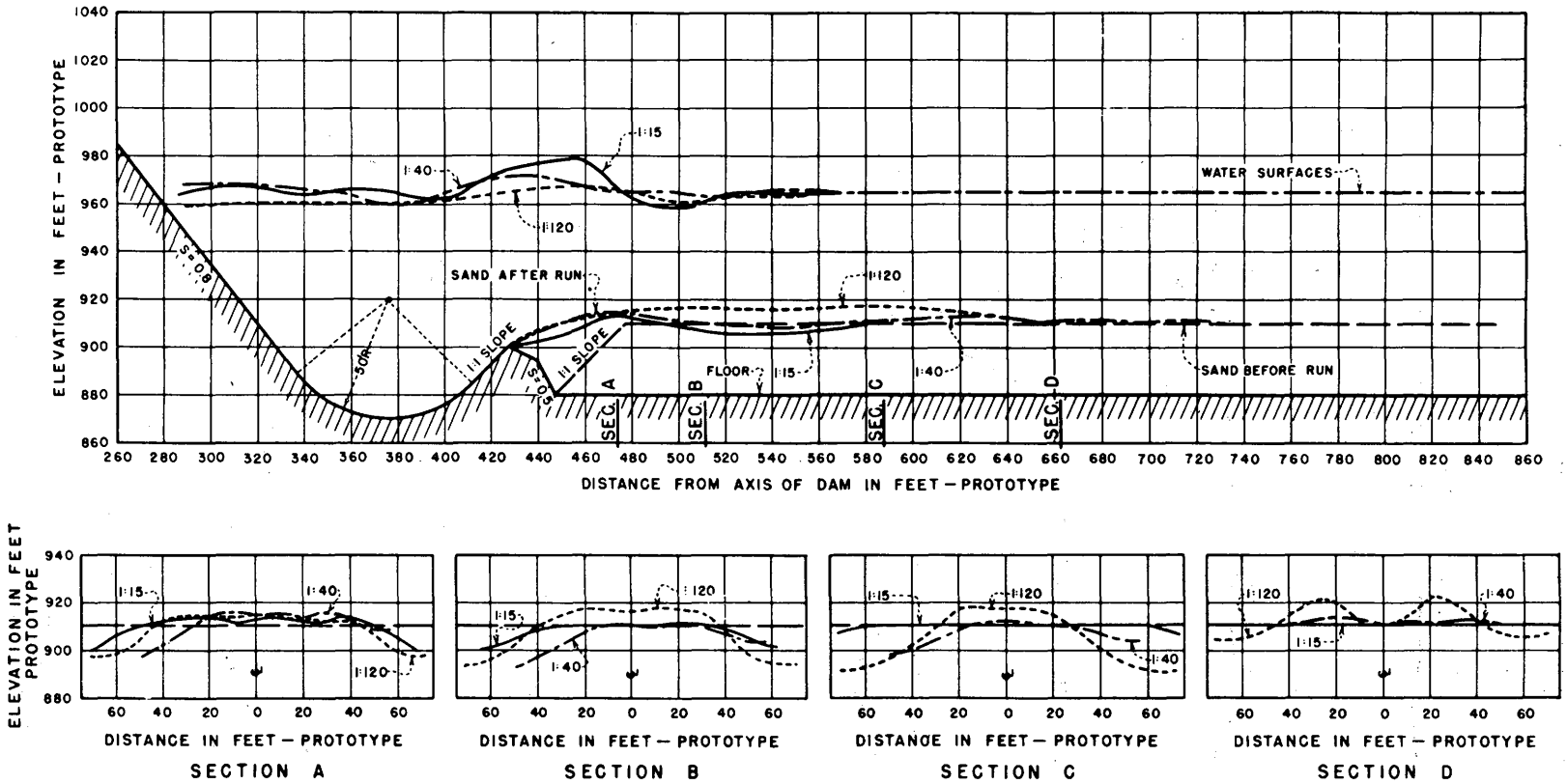
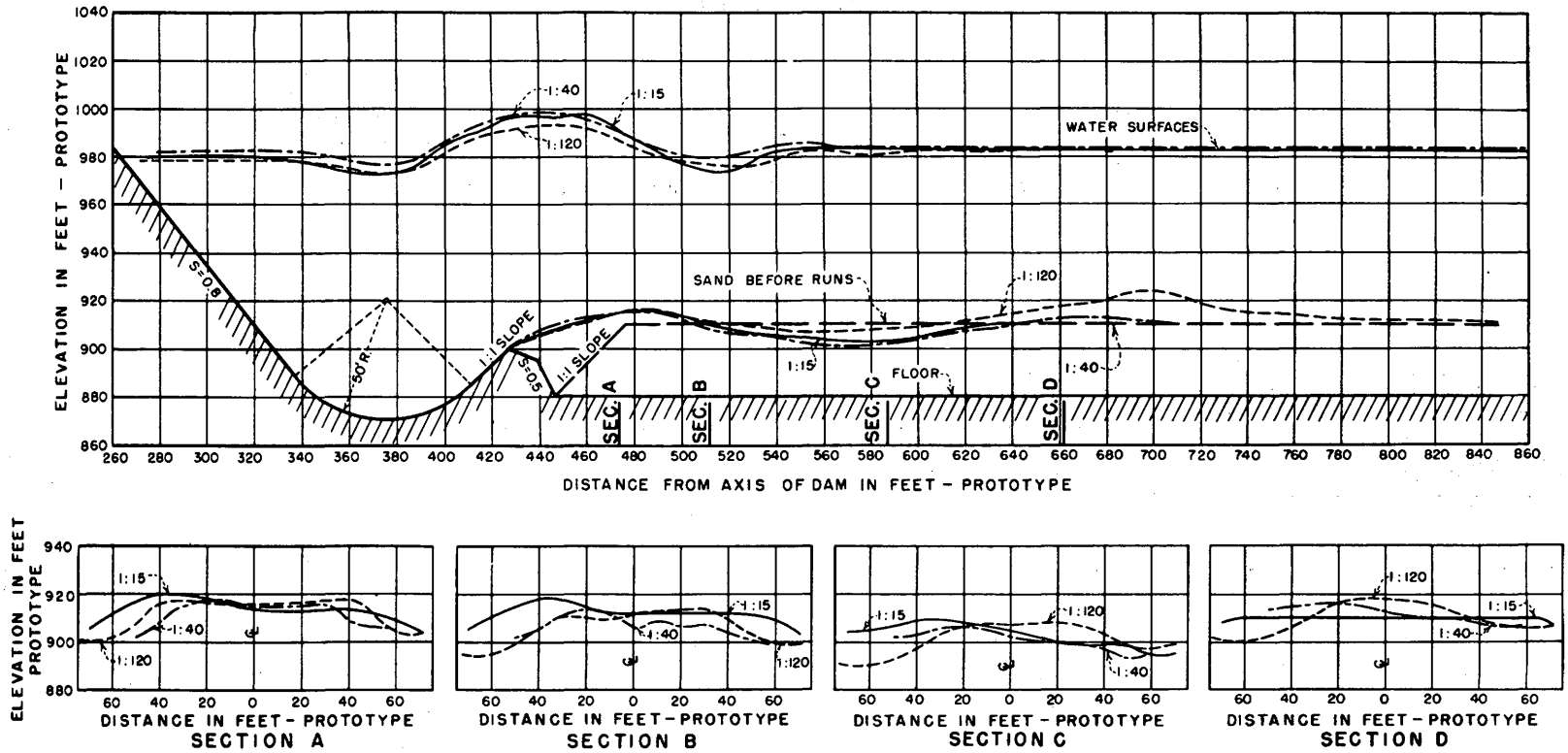


FIGURE 7
COMPARISON OF PRESSURES ON ENERGY DISSIPATOR



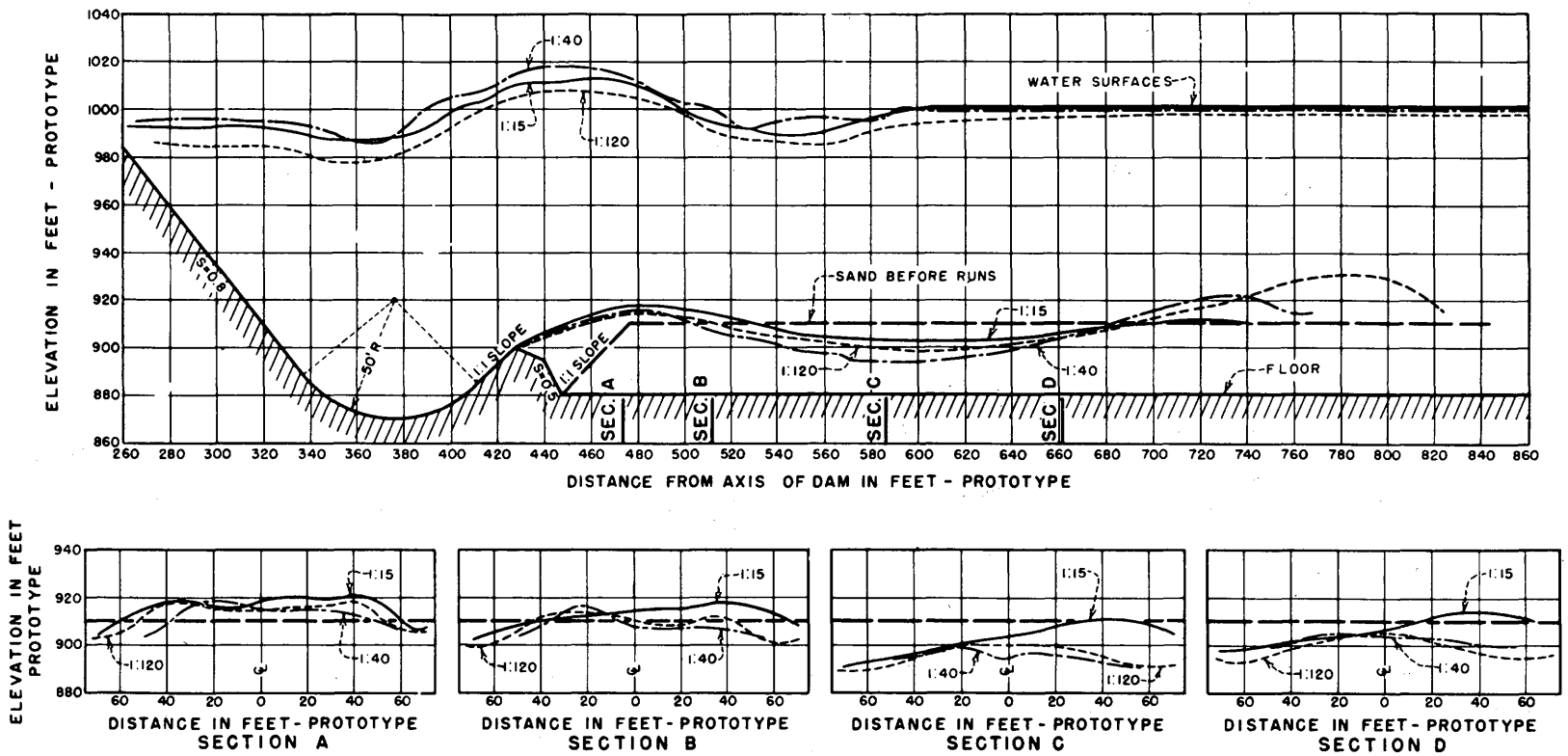
SYMBOL	SCALE RATIO	LENGTH OF RUN (PROTOTYPE)	WIDTH OF FLUME (FEET PROTOTYPE)
———	1:15	19.48 HRS.	150
—·—·—	1:40	19.40 HRS.	120
- - - - -	1:120	19.35 HRS.	150

FIGURE 8
COMPARISON OF SCOUR BELOW DAM - PROTOTYPE DISCHARGE = 250,000 C.F.S.



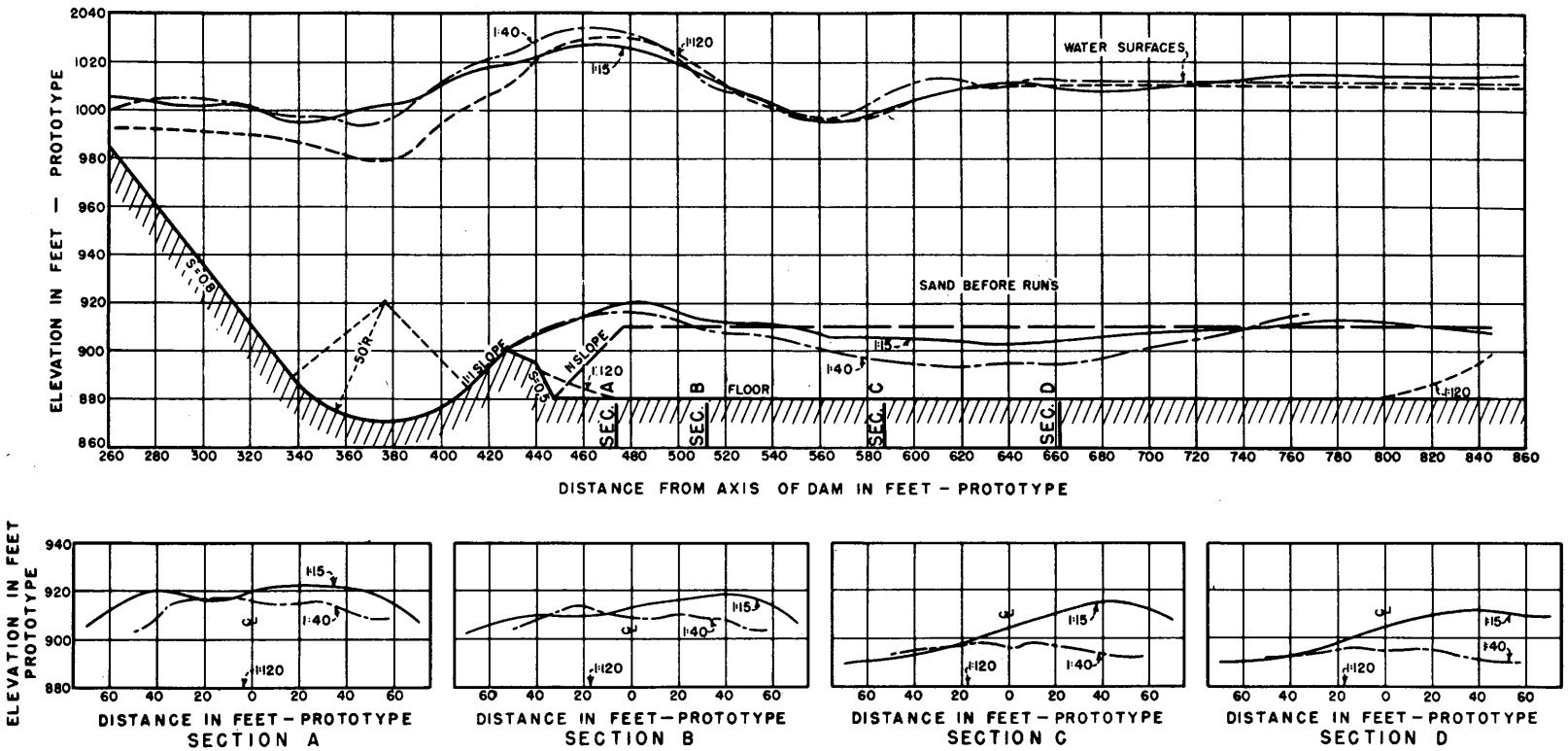
SYMBOL	SCALE RATIO	LENGTH OF RUN (PROTOTYPE)	WIDTH OF FLUME (FEET PROTOTYPE)
———	1:15	5-3.88 HRS. AND 1-19.48 HRS.	150
—·—·—	1:40	6-3.70 HRS. AND 1-19.40 HRS.	120
- - - - -	1:120	6-3.87 HRS. AND 1-19.35 HRS.	150

FIGURE 9
COMPARISON OF SCOUR BELOW DAM - PROTOTYPE DISCHARGE = 500,000 C.F.S.



SYMBOL	SCALE RATIO	LENGTH OF RUN (PROTOTYPE)	WIDTH OF FLUME (FEET PROTOTYPE)
———	1:15	1-1.00 HR. AND 1-19.48 HRS.	150
—·—·—	1:40	6-3.90 HRS.	120
- - - - -	1:120	5-3.87 HRS.	150

FIGURE 10
COMPARISON OF SCOUR BELOW DAM - PROTOTYPE DISCHARGE = 750,000 C.F.S.



SYMBOL	SCALE RATIO	LENGTH OF RUN (PROTOTYPE)	WIDTH OF FLUME (FEET PROTOTYPE)
———	1:15	1-3.88 HRS. AND 1-19.48 HRS.	150
—·—·—	1:40	5-3.90 HRS.	120
- - - - -	1:120	1-3.87 HRS. AND 1-19.35 HRS.	150

FIGURE 11
COMPARISON OF SCOUR BELOW DAM - PROTOTYPE DISCHARGE = 1,000,000 C.F.S.

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