AN INVESTIGATION OF DISTORTION

IN HYDRAULIC MODELS

A THESIS

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ABSTRACT

The purpose of this study is to investigate some of the effects of distortion in hydraulic models. An attempt is made to present a few of the problems inherent to these types of models, and to aid in their partial solution.

The literature was searched, and a brief review made, of the papers which provided information pertinent to model distortion. Limited tests were made on various sizes and types of bed materials. Two models of the same prototype were tested, one undistorted, the other vertically distorted, to assess the effect of the distortion. Finally a model was operated at various discharge ratios, to observe what effect discharge distortion had upon flow pattern and water surface slopes.

The study concludes that distortion in moveable bed models should be minimized whenever possible. Economic considerations of cost and testing time, usually dictate the choice of bed materials. Vertical distortion tends to magnify secondary currents and velocity distributions to a greater

degree than slope distortion. Structures in vertically distorted models may suffer from exaggerated side wall effect. Discharge distortion can be used to steepen the energy line in a model, thereby increasing bed load movement, or producing proper water surface slopes.

I wish to thank Professor E. Kuiper for his counsel which aided in the furthering of my post-graduate studies, and in the writing of this thesis.

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NOTATION

The following is a list of letter symbols that are not defined when used in the text.

A = area (ft^2)

D_m = mean grain size

$D90$ = sieve size that 90 percent of the material passes

g = acceleration due to gravity (ft/sec^2)

L = length (ft)

M = Mass (lbs/g)

m = subscript denoting model

n = Manning's coefficient of roughness

p = subscript denoting prototype

Q = discharge (ft^3/sec)

r = subscript denoting model to prototype ratio

R = hydraulic radius (ft)

S = friction slope

T = time (sec)

V = velocity (ft/sec^2)

w = fall velocity (ft/sec^2)

x = vertical distortion

h, y = height (ft)

ρ = density ($lbs/ft^2/sec^2$)

γ = specific weight (lbs/ft^3)

CHAPTER 1

HYDRAULIC MODELS

The hydraulic model is a convenient and reliable tool, used in solving problems of flow, which would otherwise be difficult to compute. When combined with the experience and sound judgment of the engineer, the hydraulic model can give answers which are reliable, and which can determine with a reasonable degree of certainty, the better of two tested solutions to a hydraulic problem.

Problems of flow in straight channels, or in pipes or in any simple hydraulic system, for which formulae have been tested and proved, should never be solved in models, However, when the problem becomes so complicated, the boundary so irregular or the flow phenomena so difficult that errors in assumptions could destroy any chance for accurate results, a hydraulic model study may be considered.

Undistorted models. Hydraulic model theory is founded on the principles of Hydraulic Similitude. The ideal model would possess three types of similarity; namely geometric, kinematic and dynamic similarity. Geometric similarity exists between two objects when they have a certain ratio identical in all their dimensions. This type of similarity is common to most models, hydraulic or otherwise.

Kinematic similarity is a similarity of the velocities of all homologous parts in a geometrically similar system.

If a motion picture of a model, that was kinematically similar to a prototype, was shown, with its speed changed in the ratio of the time scales, motion identical to that of the prototype would be viewed.

Dynamic similarity exists in geometrically and kinematically similar systems when the ratios of all homologous forces in the two systems are the same.

In undistorted hydraulic models, geometric similarity exists within the boundaries of the fluid motion. Kinematic similarity will exist if certain fundamental model laws are observed. In some cases, distortions of geometric and kinematic similarity will be produced, in order to obtain specific conditions and results.

Dynamic similarity in models, very seldom exists. No model fluid is known, which has the required viscosity, surface tension and elastic modulus to satisfy the conditions theoretically necessary.

Scale ratios in open channel models are derived from the Froude Law. The Froude Law assumes that gravity is the predominating force in a turbulent open channel model, and that the fluid viscosity and surface tension are negligible. It requires that the ratio of inertial to gravitational forces in the model, should be equal to the corresponding ratio in the prototype.

$$\text{Inertia force} = Ma = \frac{\gamma L^3}{g} \times \frac{L}{t^2} = \frac{\gamma L^4}{g t^2}$$

Substituting ρ for γ/g and V for L/t, then $Ma = \rho L^2 V^2$

$$\text{Gravity force} = \gamma L^3$$

Therefore, from the above statement about the equality of these forces,

$$\frac{\rho_r L_r^2 V_r^2}{\gamma_r L_r^3} = 1$$

Since $\rho = \gamma/g$ and since g_r for all practical purposes equals unity, then

$$V_r / \sqrt{L_r} = 1 \qquad \text{or}$$

$$V_r = L_r^{1/2} \text{ -------------- } (1)$$

Also, since $V_r = L_r / T_r$

then $T_r = L_r^{1/2}$ -------------- (2)

All model to prototype ratios can be obtained from equations (1) and (2). The more frequently used of these relationships, are shown as follows:

Length Ratio		$= L_r$
Area Ratio		$= L_r^2$
Volume Ratio		$= L_r^3$
Time Ratio	(T_r)	$= L_r^{1/2}$
Velocity Ratio	(V_r)	$= L_r^{1/2}$
Discharge Ratio	(Q_r)	$= L_r^{5/2}$

In order for the Froude Law to be valid in a hydraulic model, every effort must be made to minimize the effects of surface tension, viscosity, and elasticity. This can be done by keeping the velocities and depths as large as possible. For financial reasons, the dimensions required may sometimes not be feasible in an undistorted model. It is then that a distorted model may be considered.

Distorted models: Open channel models may be distorted in any of their three dimensions, with vertical distortion being used most frequently. They may also have the longitudinal horizontal scale at a different ratio than either the vertical or transverse horizontal scales.

Some models use a slope distortion. This is commonly known as "tilting". A discharge distortion may be used, as a simple alternative to tilting. While holding the water level at a desired point constant, the discharge is increased. This results in a slight steepening of the water surface slope, which may for many purposes be neglected.

Figure 1 gives an isometric view of these various forms of distortion.

The advantages of having a distorted model are listed as follows:

(1) The depth, wave height, slopes and velocities are all exaggerated, and more easily measured.

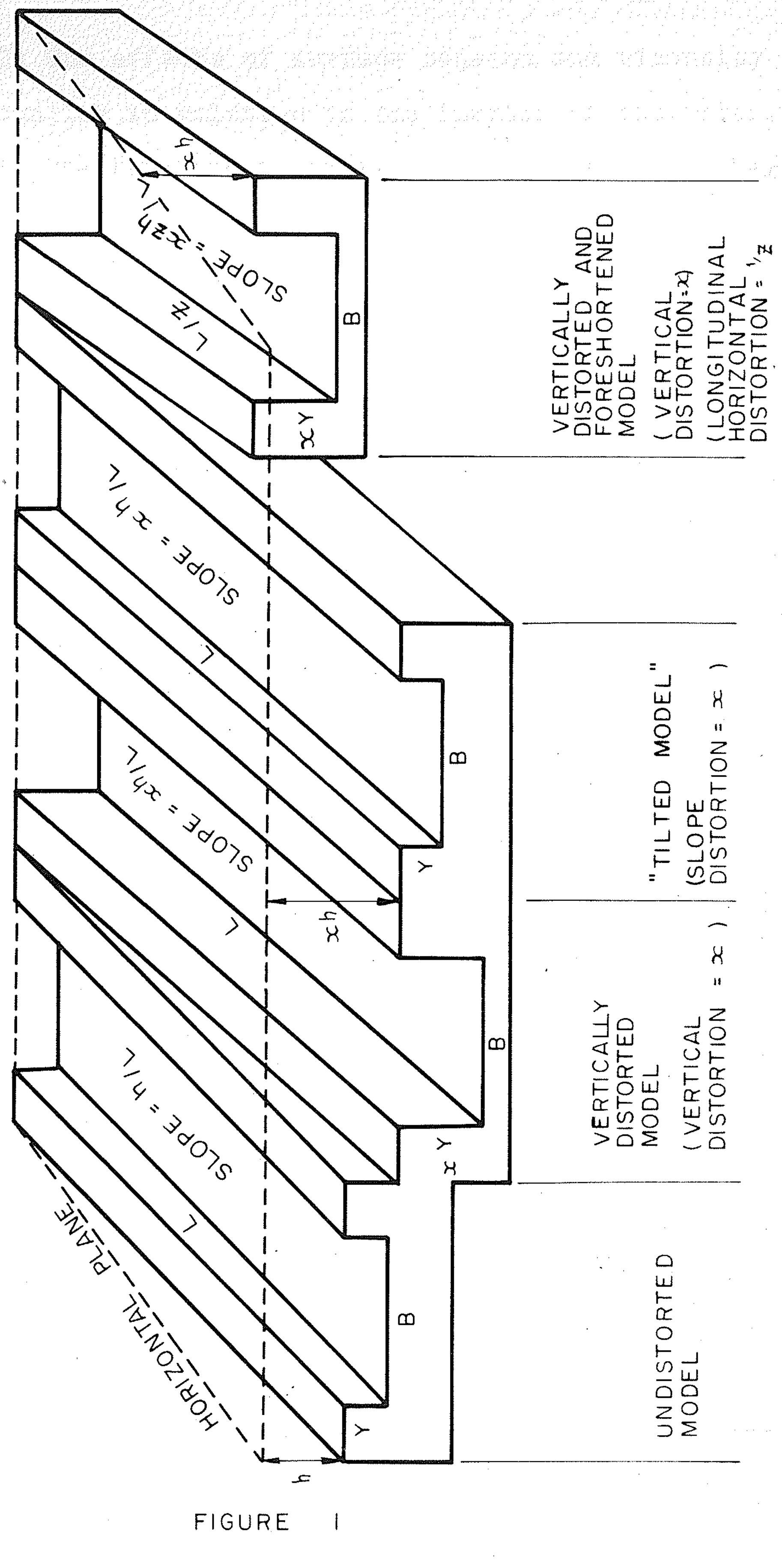


FIGURE 1

ISOMETIC SKETCH OF VARIOUS TYPES OF DISTORTIONS

(2) The effects of surface tension and viscosity become smaller in relation to the inertia of the water.

(3) The tractive force is increased, so that there is more ready movement of the bed material in a moveable bed model.

Distorted models also have certain disadvantages:

(1) Their velocity distribution may be affected, changing the flow pattern in the model.

(2) The side slopes in a moveable bed model may become unstable.

(3) There can be an unfavorable psychological effect on the tester.

These advantages and disadvantages, however, are usually outweighed by the major reason for distorted models, that is, their economy. An undistorted model is preferred to a distorted model if it can be built sufficiently large. However, laboratory space or facilities may limit the horizontal dimensions of a model. If this is the case, some distortion may become necessary, in order to ensure measureable depths or velocities.

In a distorted model, the velocity ratio is equal to the square root of the vertical scale, and all the other scale ratios must be adjusted accordingly. The list of scale ratios then becomes:

Horizontal Scale Ratio		$= L_r$
Vertical Scale Ratio		$= Y_r$
Vertical Area Ratio		$= L_r Y_r$
Volume Ratio		$= L_r^2 Y_r$
Velocity Ratio	(V_r)	$= Y_r^{1/2}$
Time Ratio	(T_r)	$= L_r Y_r^{-1/2}$
Discharge Ratio	(Q_r)	$= L_r Y_r^{3/2}$

__Fixed bed models__. When the problem being studied does not involve a change in shape of the channel bottom, fixed bed models may be used. These models have the advantage of being easily constructed and maintained. They can be built to any scale distortion, since side slope stabilities are not a criteria.

When determining the required distortion ratio, for any ratio of roughness, the Manning formula can be used.

Since $$V = \frac{1.49}{n} R^{2/3} S^{1/2}$$

then $$V_r = Y_r^{1/2} = \frac{R_r^{2/3}}{n_r} \times \frac{Y_r^{1/2}}{L_r^{1/2}}$$

therefore the distortion ratio becomes

$$Y_r / L_r = \frac{n_r^2 Y_r}{R_r^{4/3}}$$

In any model, if the depth, hydraulic radius, and roughness ratio are known, then the required distortion can be calculated. On the other hand if the value of distortion is dictated by other considerations, then the necessary roughness can be computed.

Since it is difficult to predict the exact roughness for various types of beds, the "cut and try" method is usually required to obtain the final proper flow conditions. This method involves trial and error tests, with different types and amounts of roughness, until the correct water levels and slopes, in the model, are obtained.

Moveable bed models. The required roughness of a moveable bed model is usually not obtained from the Manning formula. It is instead dictated by the type of bed material used in the study, and falls within a narrow range. Distortion must be chosen from a practical standpoint, and is usually limited by the stability of the side slopes. The actual scale of model will be dictated by the hydraulic facilities available. From these standpoints actual mathematical solution of all scales and distortion is often not possible, and instead good judgment is required. Because of this, experience is almost a prerequisite in the planning and construction of moveable bed models. Also, a thorough knowledge of the prototype, can facilitate the verification procedures that may be necessary, before actual model testing begins.

In the design of a moveable bed model, the horizontal scale is dictated by the available laboratory space or discharge capacity. The distortion is limited by the discharge capacity or by the side slope stability of the bed material. The distortion is always kept to the minimum, consistent with measurable depths and velocities.

One of the more difficult problems encountered in a model design is the choice of bed material. Some attempt must be made to find a material that will move at the correct model velocity. It must be fairly uniformly sized, so that there is no sorting of the particles during the erosion of the bed. Also, it must be readily available, and as economical as possible.

Finally, after the model has been built, its verification may be necessary. In this procedure, an accurate reproduction of a prototype occurrence must take place in the model. In order to get the proper verification, different bed materials may be tried, the vertical distortion altered, or any number of the hydraulic criteria changed, such as roughness, slope distortion or discharge ratio.

In the following chapters some of the problems involved in the operation of distorted moveable bed models, will be presented, and an attempt will be made to find their partial solution. Chapter Two will give a brief review of the literature and an abstract of some research presently being carried out. Chapters Three, Four, and Five will report the results of tests, which deal with bed material, vertical distortion, and discharge distortion, respectively. Chapter Six will offer conclusions based on the literature and the tests.

CHAPTER 11

ABSTRACTS FROM THE LITERATURE

In the following chapter, some of the research on model distortion will be reviewed. Short descriptions of the articles, with direct quotations on pertinant points, will be given.

An extensive report (7) was made in 1939 by K.D. Nichols on "The Observed Effects of Geometric Distortion in Hydraulic Models". Fourteen model studies, of various scales, distortions and bed types were described. The advantages and disadvantages of distorted models were discussed, and some of the scales used in the different model studies were listed.

It was pointed out that whereas scales of 1:50 suffice in models of small rivers, scales up to 1:2000 may be necessary for rivers the size of the Mississippi. It was stated that the larger the prototype to be studied, the greater the degree of distortion that is likely to be necessary. In the foregoing models with horizontal scales ranging from 1:50 to 1:2000, the vertical scales ranged from 1:50 to 1:200. The vertical distortions varied from 1 to 20 and the slope distortions from 1 to 26.

A brief outline on the design and operation of distorted models was then given, followed by brief abstracts of the fourteen model studies and their conclusions.

One of the studies, involving several different scale models of the same prototype, concluded that "Tests conducted with equal Froude numbers gave approximately similar results regardless of scale". This was not intended as a new conclusion, since it is the basis upon which hydraulic model theory is founded. It is, however, a practical example of the validity of the Froude Law.

From various tests, the following conclusions were drawn:

> An increase in slope distortion will increase the scour resulting from a dyke.
>
> The degree of distortion affects the distribution of velocity and, therefore, would affect the relative horizontal distribution of energy and the effective tractive force.
>
> There appears to be a greater discrepancy between the prototype and the model for a high degree of geometric distortion than for a low degree.
>
> For a decrease in slope distortion the model verification was improved.

These statements all indicate that every effort should be made to minimize distortion in moveable bed models.

Comparing tests of two models of the same prototype gave the following result:

> Although the tractive force available in the two models was equal (tractive force expressed as a product of depth times slope), greater bed movement occurred in the model having the greater depth.

This would indicate, that if rapid bed movement was required in a model, vertical distortion might be a preferable alternative to slope distortion.

A model study of bed load movement at the fork of a river resulted in some interesting conclusions:

> 1) The tests indicate clearly that for equal distribution of flow, the water entering the side channel, is mainly that flowing along the bottom and one side (nearer the side channel) of the approach channel.
>
> 2) The data showed clearly that for a given depth of flow, as the velocity (or slope distortion) increases, the zone of bottom currents turning into the side channel increases in width.

The tests then conclude that the majority of bed movement would enter the side channel, and as the bed load material became finer and a greater percentage was carried in suspension, the percentage entering the side channel would decrease.

From this study, one can conclude that extreme caution should be used in the analysis of bed load movement at channel junctions, in distorted models.

In his dicussion of the results of the fourteen tests, Mr. Nichols gave a good explanation of helicoidal flow.

> Usually in an open channel the surface currents are moving faster then the bottom currents. Hence, when a change in direction occurs it takes less force to change the direction of the bottom, than the surface currents. . . . In a bend section the radius of curvature is generally less for the bottom then the top currents and this phenomenon is a part of helicoidal flow. . . . In moveable bed studies, the engineer is particularly interested in the direction of the bottom current because they are the principle determining factor in the direction and amount of movement of the bed. . . . An analysis of these studies indicates that usually greater depth or slope distortion will increase the divergence of surface and bottom currents, and that the divergence is more marked for an increase in depth distortion than for an equal increase in slope distortion.

These statements indicate that if the model has complicated flow conditions, every effort should be made to minimize distortion, and that slope distortion would seem a preferable alternative to vertical distortion, if measurable depths are already present in the model.

Various bed materials were then discussed, ranging from gilsonite, with a specific gravity of 1.03, to sand, with a specific gravity of 2.65. A graph showing the volume of material transported, versus tractive force, for the different types was given. This graph could be used as an approximate guide in the choice of bed materials, when designing a model.

As an additional aid in the selection of bed materials, some comments on lightweight aggregates were made:

> Lightweight materials have the advantage over heavier materials in that, for a given grain size, movement occurs at a lower tractive force, and that coarser lightweight material may be used instead of heavier sand to reduce the riffling and the degree of distortion. However, the apparent specific gravity and size of coal, pumice, and haydite grains change after continued use. Amber and gilsonite are very costly and extremely difficult to use.
>
> . . . .
>
> Unless gilsonite is soaked in water, shaped rapidly to conform to the model bed, and flooded almost immediately, tiny air bubbles attach themselves to the grains and cause the material to float. However, the use of lightweight material is feasible, and it is recommended as a substitute for extreme geometric distortion. Experience indicates that a combination of moderate depth distortion, moderate slope distortion, and lightweight bed material is better then the use of one extreme to the exclusion of others.

Mr. Nichols concluded that whenever geometrically distorted models are used, they should be used with extreme caution. He stated that any possible methods of minimizing distortion should be used, and that great care should be taken in the verification of these models. He recommended that undistorted models should be used whenever possible. An bibliography is given in the appendix of the paper.

Three discussions follow the paper by Mr. Nichols. Mr. Ehrgott and Mr. Vogel agreed, in their respective discussions, that although distortions should be kept to a minimum in hydraulic studies, that distorted models are many times an economic necessity. They also agreed that if they are handled properly, these models can give quite good answers.

Mr. Ehrgott discussed formulas, based on the Manning Equation, for finding the proper roughness in a model. He indicated that they should be used only in the design of a model, and that the "cut and try" method should be used in the actual construction and verification. He mentioned that the roughness factor could not be made smaller then .009 nor greater then .026 in a model without actually constricting the cross-section.

Mr. Taylor, in his discussion, was pessimistic towards model distortion. He described tests, carried out during 1935 and 1936, at the University of California. As a result of these tests, he recommended that geometrically distorted models should be avoided, whenever suitable undistorted models can be constructed at a reasonable cost.

In these tests, an arbitary prototype was constructed, with a one foot wide channel. A model of this channel, six inches wide, was also built. Baffles protruded perpendicularly from the walls of the respective channels, into the stream of flow. These baffles caused the stream lines to follow a sinuous path along the channel. The degree of turbulence caused by these baffles depended on how far into the channel they projected.

Different rates of distortion could be tested in the model by running the test at different depths of flow. Numerous tests were run at various degrees of distortion, and under different degrees of turbulence. The results of these tests, plotted on graphs, resulted in the following conclusions:

1) Undistorted models more truly represent their prototype then distorted models.
2) If the Froude Law is used as the model criterion, models of highly turbulent systems are more faithful then models of relatively smooth flows.

Mr. Taylor was pessimistic about the use of distorted models, and did not judge the verification of a model at one discharge, as sufficient proof that it would operate faithfully at other discharges. However, Mr. Taylor's opinion about distortion, although stronger, was in essence the same as that held by the other three writers. They all agreed that distortion in hydraulic models should be kept to a minimum, and that extra care should be taken in their testing and analysis.

A symposium on model to prototype conformity was presented in the 1944 A.S.C.E. Transactions. In one of the papers (3), Frederick R. Brown discussed conformity in geometrically distorted river models.

He stated that while exact geometric similitude must be maintained in models of hydraulic structures, that in river models, it is sometimes necessary to distort the vertical scale or add slope distortion in order to obtain the results desired. He further commented:

> Complete similitude is not essential if care is taken in selecting the model scales for solution of the problem at hand. If the problem is one involving channel capacities or study of flow-crest profiles, the model scales can be distorted considerably, . . . All that is necessary . . . is to adjust the model roughness in order to . . . permit the reproduction of the desired stage-discharge relations. . . . If the problem involves a movement of bed material, the distortion of model scales must not be too large. . . . If the horizontal and vertical scales selected are such that the distortion is low and the stream is wide with respect to the depth, the distortion will not alter the general shape of the channel, and a close similarity of velocity distribution will exist.

An example was given of a Mississippi River model with a vertical distortion of four, and with a slight additional slope distortion. In this model, accurate verification was established, and good results for velocity distribution and bed load movement, were obtained.

Mr. Brown then discussed the fact that exact theoretical model roughness need not necessarily be met, since the value of the roughness ratio, is inversely related to the value of the discharge ratio. From the Manning Equation the following formula is obtained:

$$Q_r = \frac{R_r^{2/3} L_r^{1/2} Y_r^{3/2}}{n_r}$$

It can be seen from this formula that for any constant value of hydraulic radius and water surface slope, that the roughness ratio is inversely related to the discharge ratio. Therefore, if the roughness present in the model does not give the correct water surface slope, the discharge ratio may be slightly adjusted to give the proper verification.

Mr. Brown ended his discussion by stating:

> All in all the distorted model provides a valuable tool for the solution of difficult problems. . . . Experienced model technicians realize the true value of distorted models and can be depended upon to intrepret the model results correctly. . . . Of the amount of information available, . . . the prototype performance is bearing out the predictions of the distorted scale models in practically every case.

At the I.A.H.R. meeting at the Hague in 1955, a report (6) was made on the "Criteria for Similitude of Scour Below Hydraulic Structure" by Wen-Hsiung Li. Two groups of models were tested, one group being of a spillway, and the other of a submerged opening. Two models of spillways and three of submerged openings were used. Seven different bed materials were used in the tests. Six of these materials were sands of specific gravity 2.65, ranging in size from 0.35 to 3.5 millimeters. The seventh bed material was an emery of specific gravity 3.81 and a mean diameter of 0.4 millimeters.

Numerous tests were run at various discharges and tailwater depths. The depths of scour were measured at frequent intervals in the first two hours of tests, and twice every hour during the remainder of the test. Most of the tests were run for six hours with some being run for twelve hours. Observations of the tests and plots of their results gave the following conclusions:

a)Under corresponding conditions of flow, the shape of scour hole at corresponding depths of scour is independent of the bed material and size of the model.

b) During the main portion of the time when the depth of scour is increasing, the scour depth is practically proportional to geometric progression of the duration of the scouring action. However, as indicated by several tests at long duration, the depth of scour will finally reach and remain at a limiting value.

c) For similitude of scour in scale models the fall velocityof the bed material should be chosen according to the velocity scale for the flow. The linear size of the bed material is not, in general, reduced according to the linear scale.

d) The rate of scour is not reduced in accordance with the velocity scale for the flow. It can be shown rationally that the scour depth is a function of $\frac{dwt}{L^2}$ instead of $\frac{wt}{L}$

The tests indicated that bed material for a model should theoretically be chosen so that the ratio of its fall velocity to the fall velocity of the prototype material, is in the same ratio as the velocity scale. They also indicated, however, that proper shapes of scour patterns will be found with any size of bed material.

It can be seen from conclusion (b), that the time scale for model testing need not necessarily be dictated by the Froude Law. It is possible, that a few preliminary runs would show the amount of time necessary, to develop the major scour patterns. Then, if various schemes which affect scour are being studied, fair comparison can be made between the alternatives, so long as identical length of time are used in the various tests. The conclusion that the depth of scour was a function of dwt/L^2, (where d equals grain diameter, w equals fall velocity, t equals time and L equals a characteristic length in the model), was found by rational considerations in the paper. A graph of the results of the tests, showing depth of scour versus (dwt/L^2) plotted on fairly smooth lines.

At the same conference a paper (1) was given by Mr. M. Ahmad of Pakistan. It was entitled the "Effect of Scale Distortion, Size of Model Bed Material and Time Scale on the Geometrical Similarity of Localized Scour".

Several geometrically distorted, moveable bed model investigations were analysed, and the following were some of the general conclusions made:

> It has been shown that in a small scale distorted model the scour is less deep and more wide than the corresponding dimensions in the prototype. In models with distortion greater than four or five the effect of distortion has to be eliminated or gauged before the model results can safely be applied to prototype.

Mr. Ahmad stated that great care had been taken in the verification of the models. With regard to the effect of the size of bed material on localized scour, Mr. Ahmad commented:

> It has been shown for scours in geometrically similar models that the rate of development of scour is much more brisk for a finer sand than for a coarser one, though the stable value of scour is more or less the same. . . . Thus by using the finer sand, better reproduction of scour depth can be obtained in a comparatively shorter time. The excessive riffling of the bed, however, imposes a limitation on the use of very fine sand.

This quotation agrees with a previous paper, in stating that the amount of scour was not a function of the size of bed material. Agreement on the rate of scour was also indicated:

> The rate of development of scour is shown to be very brisk in the initial stages of development and the scour depth approaches asymtoptically the final stable value. If the model is run for more time no appreciable increase in scour is obtained.

Mr. Ahmad then described two model studies, where several time scales were tried for each, before actual testing began. In both cases it was found that after a short time, four minutes in one and six minutes in the other, no improvement in similarity of the scour was obtained, and that the sand had reached its stable scour depth. Any increase in time scale would not be justified. Mr. Ahmad suggested that before any moveable bed model study, several tests should be run at various time scales, to decide which would be the optimum time scale to be used.

At the 1957 I.A.H.R. meeting in Lisbon, nine papers were presented on the subject of scale effect. One of the papers (5) entitled "Scale Effect in Hydraulic Research" by Joglekar, Gole, and Chitale, dealt mainly with scale effect in models of structures. However, since a structure is very often involved in a moveable bed model, some comments can be drawn from the paper.

If a structure in a distorted moveable bed model is built so that its vertical scale and longitudinal horizontal scale, are built to the same vertical scale as the model, then the proper depth and shape of flow lines will be obtained in the discharge over the structure, (assuming that the model to prototype roughness ratio is correct). The width must be built to the horizontal scale of the model.

The proper roughness in the model may be difficult to obtain, as very smooth models are necessary. Even if this roughness is obtained, side wall effects from piers and training walls can make the study very difficult to analyse. The authors gave the following alternatives, which can be used, to reduce the frictional losses to their proper proportion:

> The expedient which is therefore used in models is that of artificially increasing the discharge coefficient of the model weir by slightly steepening the upstream and downstream glacis slopes or else by reducing the length of weir in line of flow. Sometimes lowering of the sill in the model is also adopted.

These measures would have to be adopted with care and could not be used if any measurements on the structure itself were to be made.

In distorted models where there is flow around piers, dissimilarity of flow or excessive scour can occur. The authors offered the following solution:

> All these defects are overcome providing the width to depth ratio of the model span and the prototype span is kept the same by suitably reducing the number of the piers in the model. The number of the piers in the model is obtained by dividing the number of piers in the prototype by the vertical exaggeration.

This method of construction, which eliminates the distortion in the individual bays, is discussed in Chapter IV.

Another paper (9) on scale effect was given by Charles Thomas of the Bureau of Reclamation in Denver. It was entitled "Velocities, Scour and Pressure Measurements From Three Models of the Same Structure".

Three models of the spillway of the Grand Coulee Dam, were built to scales of 1:15, 1:40, 1:120. These models were constructed at different times for three different studies. At a later date, the results were grouped and analysed, to see if any observations on scale effect could be made.

Velocity measurements were taken at the centre lines of all the models, since it was felt that side wall effects would rule out any chance for comparison at the sides of the models. The following comments were made with regards to the velocity measurements:

> 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 the models was reached.

In discussing the scour studies in bed materials used in the models, some comments by Mr. Thomas bear repeating:

> In models of spillways and outlet works, . . . 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 the extent of scour which might be expected in a prototype.

This last sentence should be remembered when the results of scour tests in models are being analysed.

The types of bed materials for the three models were dependent on the largest model. The material which was readily available was used in the 1:15 scale model. The material for the other two models was chosen so that the ratios of the mean diameters of their grain sizes, compared to that for the 1:15 model, were equal to the ratio of the linear scales of the respective models. No comparisons could be made from the results of the scour tests. Mr. Thomas stated that "The basic assumptions made in regard to scale relationship of the mean grain size was not born out by the observations".

As was quoted earlier in the chapter, a better criteria for the choice of bed material would be the ratio of fall velocities, rather than the ratio of the mean grain size diameters.

The last article consulted (11) was a special research report issued by the U.S. Corps of Engineers on a "Triangular Flume Study of Distortion Effects". It is part of a continuing research program on model distortion, being carried out by the Corps. A brief abstract of this report is given here. An investigation was carried out to try to evaluate the effects of distortion in model studies, with the aim of establishing distortion limits for various models.

The literature was explored, but although distortion was discussed frequently, very little dealt with its specific effect.

Exploratory tests were made on prototype and model rectangular flumes. However, it was found that inaccuracies in simulating entrance and exit conditions, and in taking measurements, obscured the small variations which should have resulted from different distortions.

Tests were then run in a triangular flume. They were successful in establishing the influence of channel shape on the channel resistance function.

A sixty-five foot flume was built with two foot side walls of plywood, joined at the bottom by a continuous waterproofed hinge. The flume was supported by a seven inch I-beam resting on nine jacks. The transition from the stilling basin to the varying central angle of the flume, was made with special sheet metal.

Water surface measurements were made with a point gauge riding on parallel rails, discharge measurements with two Venturi meters and a three inch Van Leer weir.

Velocity measurements were made with a specially designed pitot tube attached to a modified Wahlen gauge. Velocities measurements could be taken as close as 0.02 feet from the wall, over a range from 0.3 to 5.0 fps.

With this apparatus, any number of angles (and consequently distortions) could be investigated with the added advantage that small depths of flows in the flume were in effect models of the larger depths.

A series of tests was run with smooth varnished walls, using four central angles. 137 degrees was considered prototype, and three smaller angles down to 40 degrees gave distortions of 1.75, 3.50 and 7.00. Each angle was tested at three slopes and four depths.

Tests were also run on a rough flume, using $\frac{1}{4}$ inch square by 9/32 inch high plexiglax parallelepipeds at $1\frac{1}{4}$ inch spacings for roughness. The same tests as in the smooth flume were run, and in addition maximum depths and steeper slopes were tested.

Data from the smooth flume showed discrepancies which were thought to occur in discharge measurements. The meters and weir were carefully calibrated.

The rough flume tests were more accurate, but some deviations were still in evidence. To minimize these deviations, plots of d vs Q were made which proved to be straight lines on log-log paper.

Revised data from these plotted points varied very slightly in most instances, but proved to have some significance in some of the analytical plots.

A general resistance equation was sought, to express the depth of flow as a function of discharge, slope of flume, roughness and shape of channel.

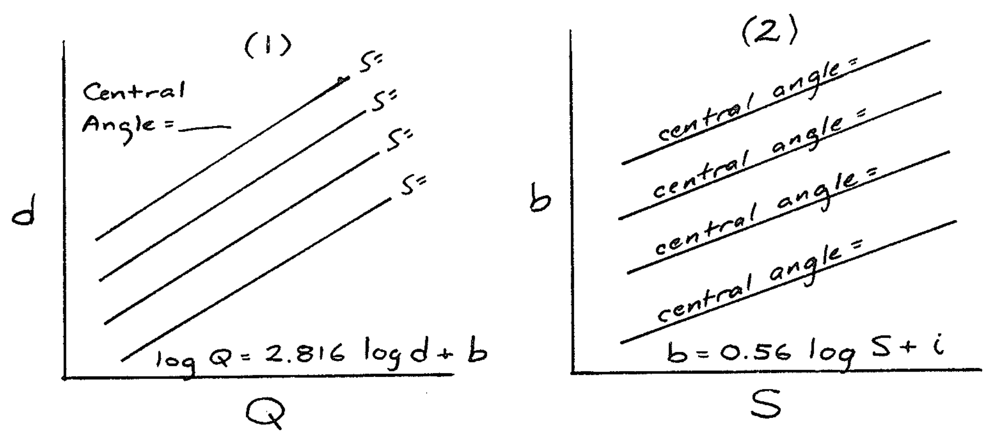
The plots of d vs Q gave the equation:

$$\text{Log } Q = 2.816 \log d + b \text{ ------- } (1)$$

From Manning $$Q = \frac{1.49}{n} A R^{2/3} S^{1/2}$$

Since A is a function of d^2, and R is a function of d, it is found that the slope should have been 2.667. It was decided that either Q does not vary as $R^{2/3}$ or that n varies with the depth of flow.

The intercept b in equation (1) is a function of both the slope of the flume and central angle. A plot of b versus S for all central angles was made,



and the following equation determined,

$$b = 0.56 \log S + i \text{ -------- } (2)$$

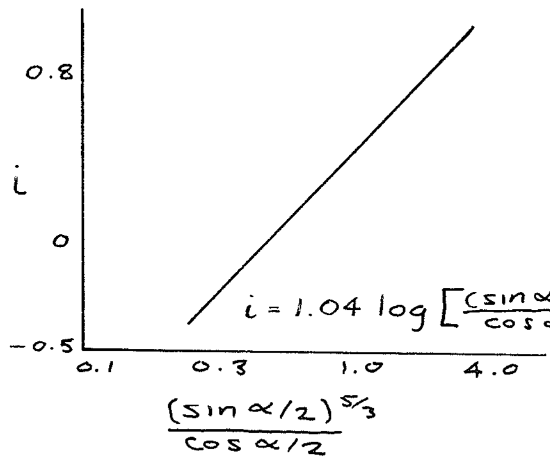
(where i is a function of the central angle of the flume).

From the Manning formula it can be seen that

$$Q \text{ varies with } \frac{(\sin \alpha/2)^{5/3}}{\cos \alpha/2}$$

i was plotted against $\dfrac{(\sin \alpha/2)^{5/3}}{\cos \alpha/2}$

where α = central angle of the flume



$$i = 1.04 \log \left[\frac{(\sin \alpha/2)^{5/3}}{\cos \alpha/2}\right] + c \quad ----(3)$$

Substituting equations (2) and (3) in equation (1)

$$\log Q = 2.816 \log d + 0.56 \log S + 1.04 \log \left[\frac{(\sin \alpha/2)^{5/3}}{\cos \alpha/2}\right] + c \quad ---(4)$$

Since all these tests were run with the same spacing and size of artificial roughness, no indications of the effects of pattern, spacing, size, shape of roughness showed up in the formula.

However, since it is common practice to use a single linear measure to express absolute roughness, it was assumed that a term involving k (height of roughness elements) to a power could be incorporated in (4).

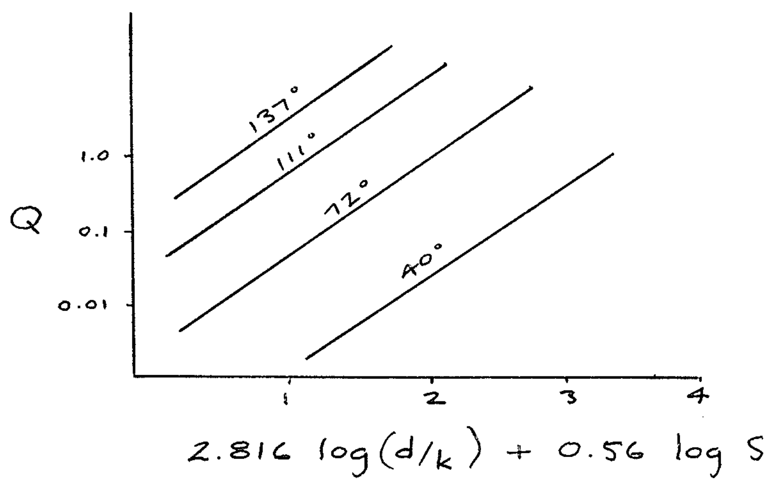
This led to the final equation

$$\log Q = 2.816 \log(d/k) + 0.56 \log S + 1.04 \log\left[\frac{(\sin\alpha/2)^{5/3}}{\cos\alpha/2}\right] + 2.59 \quad ---(5)$$

The effect of distortion was shown as the central angle changed by removing the shape correction term

$$\left[1.04 \log\left\{\frac{(\sin\alpha/2)^{5/3}}{\cos\alpha/2}\right\} + c\right]$$

The data was then plotted as a function of relative roughness and slope only.



The conclusions of the study are listed as follows:

(a) The study was successful in establishing quantitatively the influence of channel shape on the channel resistance function, for the cases in question. Further analysis of these and additional date should establish principles to triangular shaped channels.

(b) The value of absolute roughness (k) of a channel is not enough to describe the effective roughness. Channel shape should also be specified.

(c) The variations of the drag coefficients of the individual roughness elements with their respective Reynolds numbers in small channels is not dependant only on the square law of resistance, but also on velocity gradients, shape and height of roughness elements, angularity of flow, and surface texture of the channel bottom.

(d) Increasing the distortion greatly magnifies the intensity of secondary or transverse currents, thereby affecting the similarity of velocity profiles.

Continuation of studies should provide parameters which could establish limits and effects of distortion. However, many more extensive tests would be necessary.

General Conclusions from the literature. Some of the conclusions that were found in the literature, that seem to meet with general agreement, and that could be applied to all model studies will be briefly summarized here.

(1) A distorted model should never be used in a moveable bed model study, if an undistorted model can be built at reasonable cost. If distortion is necessary, every effort should be made to minimize its effect.

Distortion is more likely to be necessary, as well as tolerable, in models of large rivers, with their low depth to width ratios.

(2) The bed material grain size should not be chosen according to the linear scale of the model. It has been suggested that the fall velocity of the material should be dictated by the velocity scale ratio. However, tests have shown that scour is independant of the type of material. Since fine sands erode more rapidly than coarse, as fine a material as possible should be chosen, the limit being placed when rippling begins. Preliminary tests can aid in this choice, and can determine the time scale necessary to establish stable scour patterns. The use of light weight aggregates is not recommended, but it is preferable to extreme geometric distortion.

(3) Less disturbance of flow pattern is likely to occur in a slope distorted model, than in a vertically distorted model. Increasing the distortion of a model, magnifies its secondary currents, thereby affecting its velocity patterns. In two models with equal tractive force (depth times slope), greater bed load movement will take place in the vertically distorted model, than in the slope distorted model.

4) Greater care is required in the verification and analysis of distorted moveable bed models, especially if they involve bed load movement near channel junctions. The theoretical model roughness ratio ($L_r^{1/6}$) need not be exactly attained, since a change in the discharge ratio can result in the required water surface slope. Turbulent models tend to give more reliable results than smooth flowing models.

5) Structures in distorted models should be built with their longitudinal horizontal scale identical to the vertical scale. Many improvised solutions can be used to decrease the exaggerated side wall effect, and thus improve the discharge coefficient. However, most measurements on these structures should be of a preliminary nature only.

CHAPTER III

CHOICE OF BED MATERIAL

Preliminary studies. When a model of the Red River Floodway was to be built at the University of Manitoba in 1962, one of the most important problems to be solved was the proper choice of bed materials.

A tour was made of three major hydraulic laboratories in the western United States: St. Anthony Falls, Minneapolis; Iowa Institute of Hydraulic Research, Iowa City; and the United States Bureau of Reclamation, Denver. At each visit, the proper procedure for the choosing of bed material was requested. At all the laboratories there was general agreement that no standard procedure for making this choice exists, and that instead, the experience and good judgment of the tester is required.

The laboratories visited, generally used sand of fairly uniform grain size for their model bed materials. Various sizes of sand were used, as dictated by the model study, but they were always chosen of sufficient grain size to avoid rippling. A review of the literature showed that the majority of North American hydraulic laboratories followed no theoretically-developed procedure for choosing bed materials.

It had been suggested while on the tour that European laboratories had developed a standard practice for choosing bed materials. Requests for information on this subject were sent to several European laboratories and some literature was received from the Centre de Recherches et d'Essais de Chatou, France. In their Bulletin of 1962, a paper was presented by J. L. Chauvin entitled "Similitude in Moveable Bed River Models"(3).

In his paper, Mr. Chauvin establishes similitude formulae for models, based either on the logarithmic head loss relations, or on a generalized monomial formula similar to Strickler's formula. A nomograph based on these formulae is shown in Figure 2.

Once two invariants for the model have been chosen (for example, horizontal and vertical scale ratios), all the other model scales, including size and type of bed material can be determined from the nomograph. Two observations can be made about the choice of bed materials, using the nomograph:

1. If the model is undistorted, regardless of scale, the ratio of the specific gravities of bed materials under water, equals one. Also the ratio of their grain sizes is the same as the model scale ratio.

2. If the model is vertically distorted, the ratio of the bed material specific gravities under water, increases in proportion to the square of the distortion

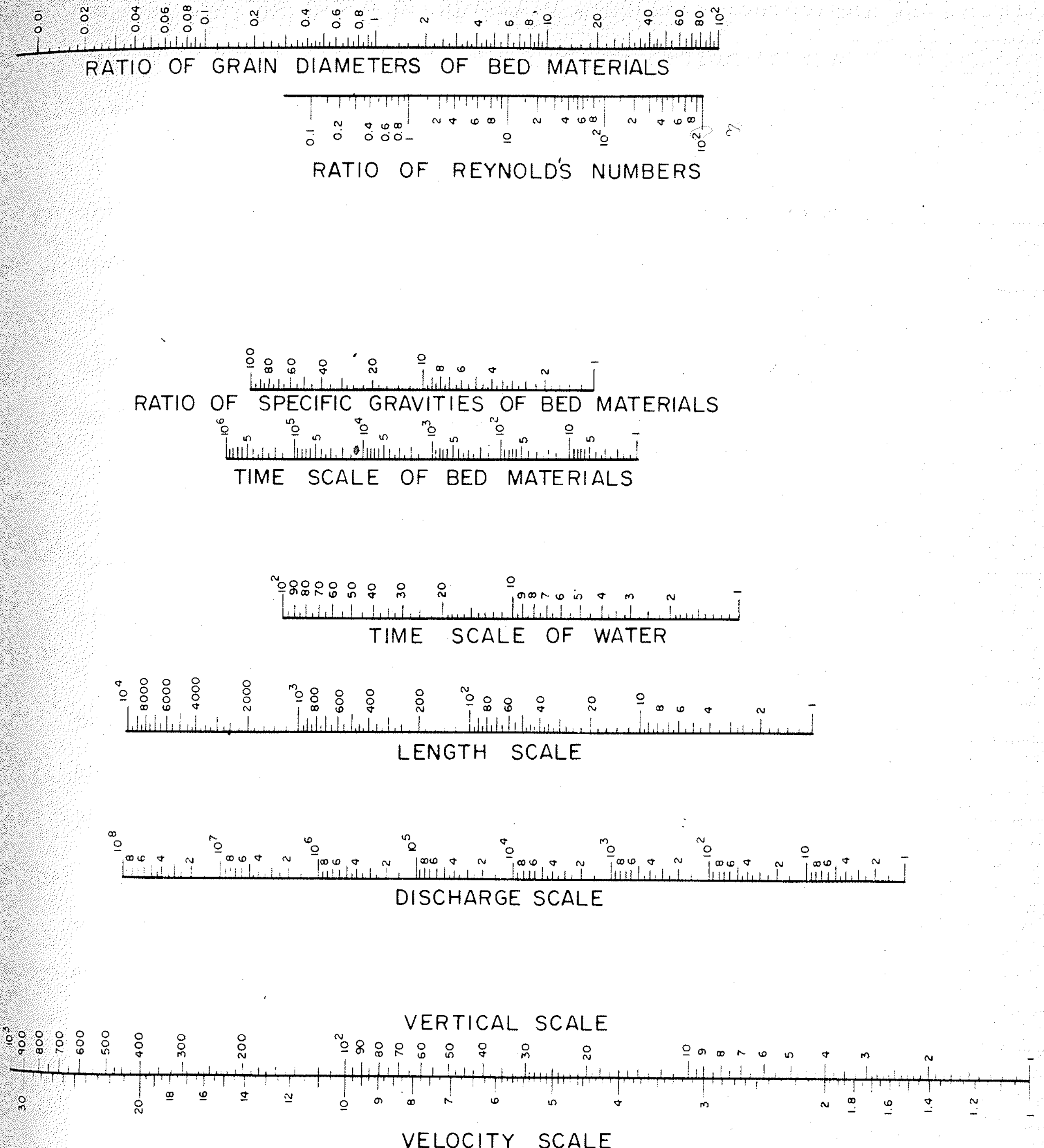


FIGURE 2

NOMOGRAPH OF MODEL SCALE RATIOS

ratio. As the ratio of specific gravities increases, the ratio of grain size decreases, in proportion to the inverse square of the specific gravity ratio.

It can be seen, that using the nomograph for the choice of bed materials, in undistorted models, would result in prohibitively small model grain sizes, unless the prototype bed was of a gravelly or rocky nature. Also, the nomograph dictates that lightweight aggregates be used in distorted models.

The Red River Floodway Outlet Model was to be built to an undistorted scale of 1:100. The bed material in the prototype was composed of fine sand and silt. Use of the nomograph would have dictated a bed material with a grain size in the fine silt or clay range. It was therefore felt, that the use of the nomograph for the choice of bed materials, was not practical for the Floodway model.

It was decided to investigate three sands, which were readily available, and of fairly uniform grain size. The sizes of these sands are listed as follows:

Fine model sand $D_m = 0.11$ mm $D_{90} = 0.17$ mm

Medium model sand $D_m = 0.15$ mm $D_{90} = 0.24$ mm

Coarse model sand $D_m = 0.28$ mm $D_{90} = 0.44$ mm

It was also decided that a limited investigation into the possibility of using coal should be carried out, in case no practical sand could be found for a bed material. Various samples of lignite coal were seived into uniform sizes, ranging from 0.5 millimeters up to 10 millimeters. No investigation of other lightweight aggregates was attempted, since their changeable properties tended to rule them out of large scale model studies.

Flume tests. A one foot wide flume was constructed, with smooth bottom and sides. A depression about two inches deep, for a length of one foot and the full width of the flume, was placed at the mid-point of the flume. The material to be tested was placed in the depression, and smoothed off with its top level to the flume floor.

Each test started with a depth of flow through the flume of four inches, at close to zero velocity. The velocity was slowly increased, while the depth was held constant. Visual observations were made as to when erosion began. It was hoped to obtain a material that would begin to erode at 0.8 fps, at a depth of about four inches. These conditions corresponded to a prototype velocity of 8 fps, at a depth of thirty-five feet, which were the assumed prototype conditions for erosion.

The two millimeter coal eroded at the proper velocity, but was a very dirty material with which to work. It tended to clot into masses, and much of it would float when the flume was being filled. In addition, it was very expensive to obtain in the narrow range of seive sizes required. Coal was therefore eliminated from further study.

The three sands tested began eroding in the right velocity range, (fine - 0.7 fps, medium -0.8 fps, coarse -1.1 fps,). However, it was very difficult to judge how this erosion would appear in the large model, due to the limited area of observation. It was decided that a larger test section would give a better assessment of the bed materials.

Preliminary model tests. A model of the drop structure to be tested in the main study, was built in a three foot flume, with four hundred feet of channel modelled downstream. The structure was built to the same scale as that required for the large model, that is 1:100. The downstream channel was built up for each test with one of the various sands to be tested.

Test runs were made at the design discharge for the structure. These tests resulted in the choice of the medium sand for the large model, although the differences between the sands were slight. However, the coarse sand appeared to give little erosion, and the fine sand tended to slump when wetted.

Model tests. The sands had shown some slight tendency to ripple in the preliminary model, but at the time, this did not appear to be any problem. However, when the large model had been built, the medium sand modelled and the first test completed, it became apparent that the sand chosen was too fine grained. Extensive rippling had taken place in the eroded areas.

After two tests, some of the reasons why this type of erosion was not desirable could be seen:

1) Approximately four hours were required to lay the contours, because of intricacies of the erosion patterns. This length of time created difficulties, since the slow leakage from the model had to be continually balanced by adding water. (The contours were laid with wool yarn along the water line, the water level being dropped in regular intervals).

2) Comparing the results of two tests became nearly impossible, since the meanderings of the contour lines completely confused the overall pattern. There was no clearly defined limit to the area of erosion.

3) Because of the rippling, the roughness of channel increased. This resulted in a possible change in any

or all of the flow conditions (depth, surface slope, velocity), with the resulting change in flow pattern.

There was on hand some coarse sand not intended for the model studies, but for use in the mixing of mortar for construction. The "model" sand was removed and replaced by the "mortar" sand. The "mortar" sand had a mean grain size of 0.7 millimeters, and a D_{90} size of 1.7 millimeters.

A test was repeated, resulting in a much improved erosion pattern. However, some slight rippling still occurred, due to the partial sorting of the finer particles.

The "mortar" sand was removed, and sieved through a 1.0 millimeter screen. This resulted in a "sieved mortar" sand with a mean grain size of 1.5 millimeters and a D_{90} size of 2.3 millimeters.

The previous tests were repeated, resulting in a simplified erosion pattern. There was no rippling action, and the deposition from the scour took place as one clearly defined dune. The contours were quickly laid, as they were now smooth curving lines, and slight leakage from the model during this time became negligible. There was no problem in comparing the length and height of dune, caused by various alternatives of design, and by various flow conditions. The plotting of the eroded and uneroded cross-sections became a relatively easy job.

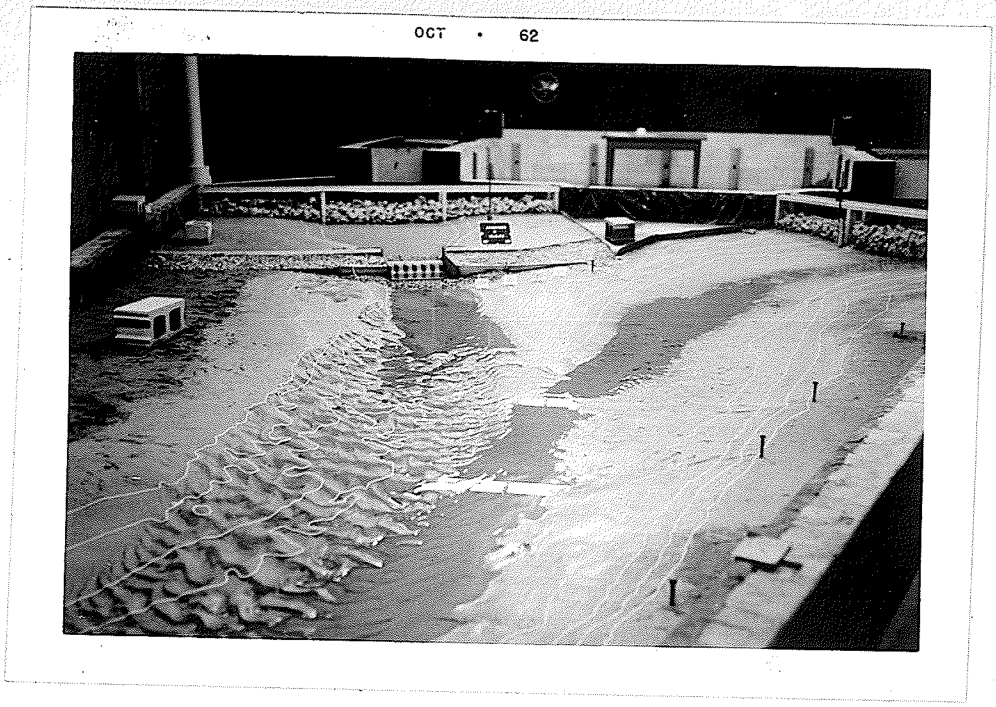
Figure 3 shows a comparison of erosion patterns for the two types of bed materials, under the same design and flow conditions.

General conclusions. Some general conclusions regarding the choice of bed materials, that may be drawn from these limited tests and the literature, will be listed as follows:

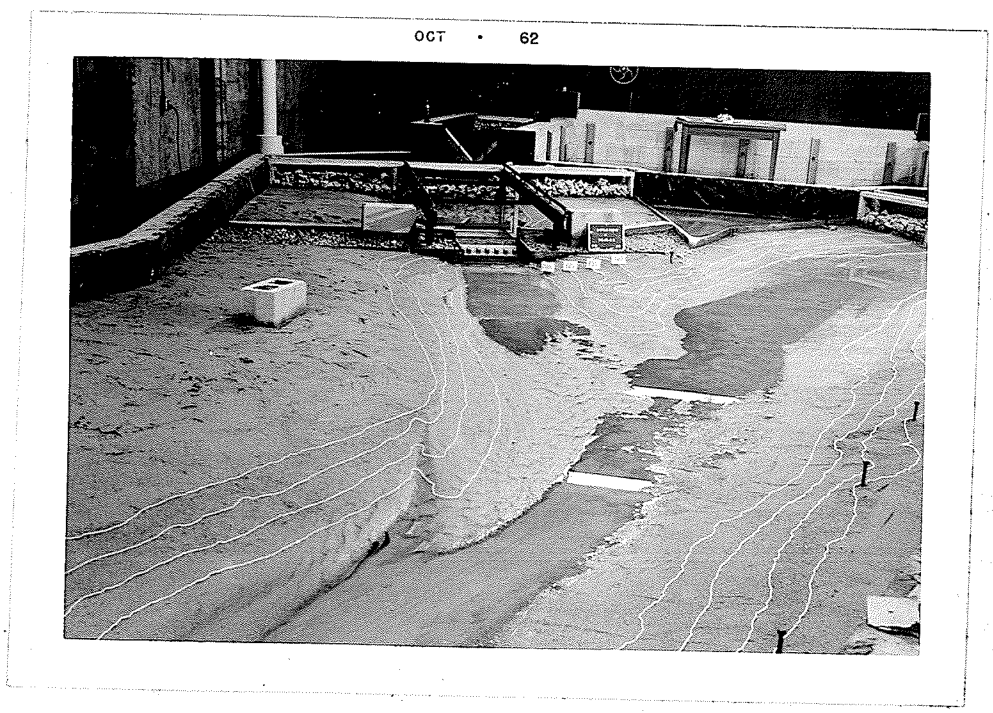
1) Such lightweight materials as pumice and sawdust should usually be avoided, since their specific gravities tend to change under prolonged exposure to water.

2) Coal is a very dirty material when used in a circulating laboratory system. In a system where the water is only used once and then discharged, this problem is overcome. There is a tendency for the particles to float in clusters, as the model is being filled.

3) Crushed plastics are a very clean material with which to work. They have a variety of specific gravities, from bakelite at 1.40 to styro-plastics at close to 1.00. Their specific gravities do not change under exposure to water. However, the cost of plastics for bed materials is relatively high. They should be considered only for very small models, or as a necessary measure to avoid extreme distortion. They have been used successfully for suspended sediment studies.



"MEDIUM MODEL" SAND



"SIEVED MORTAR" SAND

FIGURE 3

COMPARISON OF EROSION PATTERNS

4) Sand or crushed stone appear to be the widely accepted bed material used in hydraulic model studies in North America. No standard practice is followed in choosing the proper grain size, and experience is a valuable asset when performing this task.

5) If an attempt is to be made to actually predict the quantity of scour in the prototype from the results of the model study, it has been suggested that fall velocity of the bed material should be chosen according to the velocity scale of the model. Great care should be taken in the verification of this type of model.

6) The majority of moveable bed model studies are carried out for the purpose of comparing the reaction of alternative man-made hydraulic structures, on the regime of a channel. For these studies, verification of the model is not as important. In the interests of keeping the required testing time to a minimum, as fine a material as possible should be chosen, the limit being set by the occurrence of rippling. The material should be reasonably "one-sized", (a uniformity modulus less than two), to avoid the premature movement of the finer particles, which would result in sorting.

7) Preliminary flume tests can aid in the choice of the bed material, but may give a misleading picture of its rippling qualities.

CHAPTER IV

VERTICAL DISTORTION

Methods of distortion. In open channel models, unless a very large scale is used, some type of distortion is often required. Vertical distortion is the most common method used. In this type of distortion, the vertical scale is made larger than the horizontal scale.

Vertical distortion usually becomes necessary because of limited laboratory space, pumping facilities, or available funds. With the horizontal scale reduced for any of the above reasons, vertical distortion may be used to ensure measurable depths and velocities, to offset the relatively higher model resistance, or to guarantee turbulent flow.

Other types of distortion can be used instead of, or in addition to, vertical distortion. The model may have its slope distorted (commonly known as "tilting"). For this method of distortion, the model scales remain constant, but the whole model is tilted in the downstream direction. The model may also have its longitudinal horizontal scale decreased. This results in a foreshortening and tilting of the model at the same time.

Any combination of the above types of distortions may be used in a model study. However, as the degree and number of distortions increase, the model becomes more difficult to analyse, and its reliability decreases. For this reason, the majority of model studies are carried out using only vertical distortions or tilting. Of these two methods, vertical distortion is the more common.

Vertical distortion. In this chapter the problems inherent to vertical distortion will be presented, and a comparison of a distorted and undistorted model study will be made. In the next chapter, tilting will be discussed, as an alternative to discharge distortion.

Along with advantages of distorted models there are certain disadvantages which must be tolerated. Flow patterns and velocity distributions may be affected. Additional roughening may become necessary to offset the effect of steepened slopes. If structures are located in the model, some adjustment must be made to the structure, and danger of a change in flow conditions, and in interpretation of results is always a possibility. To attempt to assess these effects, two models of the same prototype were tested. One model was built to an undistorted scale of 1:60 while the other model used the same vertical scale, but had a vertical distortion of two.

Distorted structure. A model of the Red River inlet control structure was built at the University of Manitoba. The model, built to a scale of 1:120, with a vertical distortion of two, was of the structure, one mile of river downstream and one and one-half miles upstream. About one-half mile upstream of the inlet structure, the entrance to the floodway was modelled.

The structure itself, was built to vertical, and longitudinal horizontal scale of 1:60, and a lateral horizontal scale of 1:120. This gave proper depth of flow over the structure, as well as the proper vertical curvature of flow.

This model was built to study any erosion and flow distribution problems which might occur with the building of the structure. In addition, water surface profiles were recorded to give approximate rating curves.

Alternate methods of structure distortion. In addition to the type of structure distortion described above, other methods can be used in distorted models. One other alternative that can be used for models of this type, is that where the number of gates in the structure are divided by the degree of distortion. This type of solution is meant, strictly speaking, to apply to a structure with a large number of bays. For example, if the structure contains eight bays, the required degree of distortion is two, four bays are built in the model. If a distortion of four is required, two bays are investigated. In this way, the same width of structure is obtained as in the previous alternative, as well as the same curvature of flow. However, the individual bays are not distorted in any way. Instead of investigating the proper number of bays at half their natural width, one would investigate one-half the number of bays at their proper width.

The above mentioned method is not valid if the distortion, and the original number of bays are equal, and if the flow around a centre pier is to be investigated. In this situation, the structure would have to be modelled with a half pier at one side of the structure, or with the whole pier, and part of the adjacent bay in which no flow would be allowed. In either case, the flow pattern at the nose of the pier would probably be disturbed. If, however, it is considered that flow patterns are of secondary consideration compared to proper water levels through the structure, it is possible that the decreased side-wall effect of this type of model would more than compensate for the disturbed flow pattern.

A third alternative can be used, which allows flow around the pier as well as an undistorted bay, at the slight concession of space. If the horizontal scale and discharge scale are increased by twenty-five percent, then one and one quarter gates can be used on the structure. In this way, the flow at the pier nose, and in the one normal gate width, can be observed.

Undistorted model. An undistorted 1:60 scale model of the Red River Floodway inlet control structure was also built. This second model contained one and one quarter gates of the structure, with four hundred feet of river upstream and five hundred feet of river downstream.

This model was not of the type described in the third alternative above, although the same reasons for building it apply. It was simply an undistorted 1:60 scale model, which, because of space and pumping facilities, had to be built with only five-eigths of its structure and adjacent river channel modelled. Because the structure was located perpendicular to the direction of flow, in a straight and uniform stretch of river, it was felt that this method could be used, without seriously affecting the flow pattern at the structure.

The structure was built of plexiglass, (as compared to wood in the first model), to allow easy installation of piezometers on the gate surfaces.

The purpose of the second model was to obtain an accurate operating curve for the structure, to record pressure differentials on the upstream and downstream skin plates of the gates, and to study rip-rap requirements in the immediate downstream area of the structure.

Test procedures. During the testing of both models, accurate water surface profiles were taken in the structure area. Velocity measurements were taken in both models, and although the location of these measurements were different in the two studies, some comparison of the jet velocities were obtained.

Comparison of flow patterns was not possible, since the second model had such limited dimensions, and since the flow pattern could be dictated by the manipulation of the tail gates. However, the flow patterns obtained in the first model, served as a guide to the proper settings for the tail gates in the second model.

Numerous tests were performed on both models in order that an accurate analysis of all flow conditions could be obtained. For this particular study, eight flow conditions were tested in both models, under identical flow criteria of discharge, headwater, tail water, and flow pattern. These flow conditions covered a fairly large range of discharge and gate settings.

Water surface profiles were taken in seven of the tests (tests 1 to 7), giving an accurate comparison of the two models, and velocity measurements are compared in four of the tests (tests 1,2,7 and 8).

Water surface profiles. The location of the headwater reading in the first model was seven hundred feet upstream of the structure. Since this position fell out of the limits of the second model, a new one was located two hundred feet upstream of the structure. It was assumed that the difference in water level between these two points would be negligible.

From a comparison of the plotted profiles (figures 7 to 13, appendix A) and the actual measurements (figure4 appendix A), it can be seen that there was actually a change in water level between those two points, ranging from zero to one-half foot, depending on the flow.

In the calculation of discharge coefficients, the effect of this slight difference of approach depth is overcome, if one assumes that the change in discharge coefficient for a minor change in gate height, is negligible for any one flow. This being the case, the true difference between the two models can be gauged by comparing the depth of flow over the gate, instead of the actual gate height.

In general, the water surface profile in the undistorted plexiglass model entered the structure higher than the distorted model. Then, in the zone of rapid draw-down over the gate, it dropped below the profile of the distorted model. In the area below the hydraulic jump the water surface was unsteady, so that a comparison would not be justified.

By comparing the actual depth of water over the two gates, it is seen that the dischage coefficient for the undistorted model was always higher than for the distorted model. This means, that had the two gates been at the same height, the water level entering the structure in the undistorted model would have been lower.

The higher discharge coefficient of the undistorted plexiglass model, as well as the more rapid draw-down could be caused by two factors. The wooden distorted model would have a higher friction factor than the smooth plexiglass, and its narrower dimensions would give it more side-wall effect. The roughness effect would probably be the minor one, especially for the first few tests, when the varnished finish on the wood was quite smooth. In later tests, as the finish deteriorated, it might have had slightly more effect. However, the major cause for the change in water surface profile was probably the side wall effect.

As the water entered the structure, there was a pronounced draw-down at the 90 degree junction of the training wall and wing wall, as well as a lesser draw-down at the pier nose. The amount of the draw-down, especially at the wing wall, appeared to be physically the same in both models. This means, that in relation to the whole gate width, the draw-down had effect over a greater portion of the gate span in the distorted (narrower) model. This caused the lower discharge coefficients in the distorted model, as well as the less rapid draw-down at the gate.

The resulting operating curves (figure 5, appendix A) from the two models, along with the adjusted curve for the second model (adjusted for the proper approach depth) show a fair agreement. However, gate dimensions designed from model results on the distorted model would have been slightly larger, than those dictated from the tests of the undistorted model.

It can be seen from the results of these tests, that measurements cannot be taken on a structure in a distorted model, without suffering from exaggerated side-wall effect, or disturbed flow patterns. In one particular case of a structure in a distorted model, this is not true. If the original structure has a number of identical bays at least triple that of the required degree of distortion then the effects of distortion are overcome. In this case, when the number of bays built in the model are reduced, by dividing by the distortion ratio, there are at least three undistorted bays in the structure; two end bays and a centre bay. However, the majority of distorted models do not contain a structure with the above requirements. If in a particular study, the exaggerated side-wall effects are considered tolerable, then one or the other of the previously discussed methods of construction for the structure can be used. Of course, building the model to an undistorted scale is the most desirable solution, and this alternative should always be investigated first.

In distorted models containing a structure, usually only preliminary measurements are made on the distorted or reduced length of structure. Final measurements are often made on a larger undistorted model of the structure alone.

Velocity measurements. Velocity measurements in the distorted model were measured at cross-sections 130, 330, 800, 2500, and 4500 feet from the structure, to give an idea how quickly the strong centralized jet from the structure dispersed. Since the second model was scarcely 500 feet long down stream of the structure, and 200 feet were neglected because of the approach conditions to the tail gate, it was at first felt that no comparison could be made between velocity measurements taken in both models. However, a closer analysis showed that some comparison was possible.

If the distance measured in the first model, (scale 1:120) had been measured in 1:60 scale feet, the locations of the measuring cross-sections would have been at 65, 165, and 400 feet instead of 130, 330 and 800 feet.

Since both models were built to the same vertical scale, they both discharged water from the structure at the same rate per inch of width, into the same depth of tailwater, for the same prototype discharge. Also, with the structures situated in the centre of a fairly wide, flat bottomed river, it was decided a comparison could be made for an appreciable distance downstream. This was possible because the main jet remained fairly well concentrated in the centre of the river, with return eddies occupying both banks.

When point velocities of the fastest part of the jet, were plotted against distance from the structure, (in both cases to a scale of 1:60), there was close agreement between the curves. (figure 6, appendix A) If the results from the distorted model had been plotted to their proper scale of 1:120, the high velocities would be shown twice as far downstream.

This comparison indicates that distorted models might tend to give exaggerated velocity measurements and erosion patterns downstream of the structure, especially if the main jet from the structure remained confined.

General conclusions on vertical distortion. Distortion in hydraulic models should be avoided if possible, and minimized if found necessary. If a structure is incorporated in the model, several methods can be used to keep the shape of flow lines, and the depth of flow approximately correct. However, because of the usual increased side-wall effect, measurements on, and in the near vicinity of the structure, should be of a preliminary nature only. Final measurements would then be made on a larger undistorted model of the structure alone.

The results of the tests showed, that the increased side-wall effect of a distorted structure, tend to give it a lower discharge coefficient than would be indicated by an undistorted model. Also, a distorted structure may indicate higher velocities, and consequently increased scour, further downstream of the structure than would be shown in an undistorted model.

CHAPTER V

DISCHARGE DISTORTION

As was mentioned in Chapter I, one of the methods of distorting a model, is that of giving it a slope distortion, more commonly known as "tilting". However, if the model is built, before it is determined that there is a need for distortion, tilting could be a difficult procedure. A simple no-cost alternative is to give the model a discharge distortion, assuming extra pump capacity is available.

This discharge distortion is accomplished by increasing the discharge in the model, while holding the water level at the desired cross-section (possibly the mid-point) at a constant level. This will result in the increased velocities required in the model.

Advantages. It may be desirable to use a discharge distortion, for any of the following reasons:

1) To attain minimum requirements of turbulence.

2) to obtain measureable velocities.

3) to ensure sufficient tractive force.

The first two reasons are self explanatory. The last purpose may require a brief discussion here. Suppose a model has been built, and for reasons of economy, or to eliminate rippling, a coarse mortar sand is used for the bed material. The sand does not move at the velocities at which erosion is anticipated in the prototype, or scours so little that comparison between tests is difficult. One easy solution is at hand. Run more discharge through the model, keeping the water level at the area of investigation constant, until the desired amount of scour is obtained. Check to make sure the flow pattern has not changed. If it hasn't, erosion tests can be run at this new discharge ratio, and velocities can be found by dividing the measured velocity by the discharge distortion. If other measurements, such as water surface profiles are required, the test would have to be repeated at the proper (Froude Law) discharge.

An added advantage of discharge distortion, is that the model remains undistorted. Therefore, there is less danger of prejudice in the tester's judgment. Also demonstrations to people unfamiliar with the study, can be done with undistorted flows in exact replica of the prototype.

Disadvantages. There are quite naturally drawbacks to using discharge distortion, which will be listed as follows:

1) The increased discharge results in an increased slope on the water surface. This will give slightly greater depths upstream of the control cross-section, and decreased depths downstream. These depth changes will be ngligible, however, compared to the accuracy with which most velocity measurements are taken, unless an extremely long length of channel is being investigated. To compute an example, assume that the following conditions prevail in a model

Discharge	(Q)	=	1.49 cfs
Length	(L)	=	43 feet
Depth	(D)	=	0.4 feet
Width	(W)	=	6 feet
Manning "n"		=	0.016
Hydraulic Radius	(R)	=	0.35 feet
Energy Slope	(S)	=	head loss/20

From Manning's Equation, $\left(Q = \frac{1.49}{n} A R^{2/3} S^{1/2} \right)$

$$1.49 = \frac{1.49}{0.016} \times 2.4 \times (0.35)^{2/3} \times S^{1/2}$$

Therefore $S = \left[\frac{1}{(0.35)^{2/3} \times 150} \right]^2 = \frac{1}{5400}$

Therefore the head loss $= 43/5400 = 0.008$ feet

From Manning's Equation, it can be seen that the slope increases in proportion to the square of the discharge. Therefore, if a discharge distortion of 1.50 was used, the slope would be increased by 2.25. Therefore the new head loss would be

$$2.25 \times 0.008 = 0.018 \text{ feet}$$

If the water level was held constant at the mid-point of the model, then the maximum change in water level due to distortion would be

$$\frac{0.018 - 0.008}{2} = 0.005 \text{ feet}$$

This difference in water level would change the water velocity by 0.005/0.40 = 1.25 percent.

This amount of error is less than that usually experienced in most velocity measurements. A degree of accuracy of five percent is normally considered sufficient for most velocity meters. If the change in water levels approached five percent, it would not be advisable to increase the discharge distortion. Should the accurate surface profile be desired, the discharge distortion need only be reduced to one for those measurements.

2) Discharge distortion cannot be used upstream of a control structure, since the discharge coefficient controls the depth over the structure. However, if all the required measurements can be taken below the structure, then this method of distortion could be used. All measurements on the structure, upstream of the structure, and in the immediate area downstream, would have to be done with the true discharge.

3) The major drawback in distorting the discharges, is that it may result in a changed flow pattern in the model. This would destroy the very purpose of the distortion, namely to obtain a more accurate velocity distribution and scour pattern.

Discharge distortion tests. In an effort to investigate what effect, if any, discharge distortion had on flow pattern and velocity distribution in a river model, four tests were run on the outlet model of the Red River Floodway. A test was performed with an undistorted flow, and then repeated at increases in discharge of 25, 50 and 75 percent.

The model, built to an undistorted scale of 1:100, was of the confluence of the floodway outlet and the river, about 2000 feet of river upstream and downstream from this point, and about 2000 feet of floodway. Seven hundred feet upstream of the confluence, in the floodway, was a low level ogee drop structure. It was felt that if discharge distortion could be tolerated in a model of this type, it would probably be acceptable in a model of an ordinary channel.

Figure 3 gives a general view of the model.

Test No. 1 was run with 60,000 cfs in the floodway and 77,000 cfs in the river. These were the discharge conditions for which the floodway was designed.

A detailed flow pattern sketch was drawn with the aid of potassium permanganate dye tracers. A close check on the size of eddies and direction of currents was made possible with the use of premarked cross-sections in the model. These cross-sections (shown on the flow pattern sketches, figures 14 to 17,) also give the location of the cross-sections where velocity measurements were made.

Velocity measurements were made at 100 foot intervals across the bottom of the river and floodway channels, and 50 foot intervals up the banks. Measurements were taken using a Price Pygmy Current Meter, and thirty second readings. (Previous research with the meter in this model, proved that no increase in accuracy was obtained, by taking a reading over a longer interval than thirty seconds). Cross-sections showing the actual velocity readings are shown in figures 18 to 21, appendix B. Profiles, showing the compararitive velocities at the various cross-sections for different discharge distortions, are shown in figures 22 to 28, appendix B.

Water surface profiles were taken along the centerline of the floodway, in order to see how far downstream of the ogee spillway the water surface was affected by the distortion. These profiles are shown in figures 29 and 30, appendix B.

Tests Nos. 2, 3, and 4 were repeats of test No. 1, with the discharge being increased in the proportions of 1.25, 1.50 and 1.75 respectively. No further increase in the distortion could be investigated. The required water level at the mid-point of the model, could not be maintained when the discharge was increased.

Throughout these tests, the water level at the confluence of the river and the floodway was maintained at the same level.

As can be seen by the flow pattern sketches, (figures 14 to 17), there is good similarity in the flow patterns for all tests, with only a slight elongation of the main floodway eddy at the higher discharge distortions. It is realized that a sketch of this nature is only a visual observation transferred to paper. However, care was taken to refer points of current division to the aforementioned cross-section, so that later comparisons could be made.

It can be seen that the main eddy was growing slightly in size with the distortion, causing the main current from the floodway to veer slightly more out into the river. This can also be seen in the velocity profiles at cross-section V-3, where the higher distortion tests are plotted slightly more to the left. At cross-section V-2 and V-1, this effect seems to have disappeared.

In an effort to judge how much of the scatter of the plotted profiles was due to distortion, and how much to measurement errors, test No. 1 was repeated. Velocity measurements were again taken at cross-sections V-1, V-2, and V-3. The scatter of the distorted velocity profiles appears to be in the same order of magnitude as the measurement errors.

Centerline velocities were taken up to the base of the ogee spillway. (Figure 22). A plot of these velocities shows fair correlation to within fifty feet of the spillway.

Water surface profiles through the spillway (figures 29 and 30) were also taken during the tests, for academic interest only, since the depth over the structure varied with the discharge. They show that all the flows approach approximately the same supercritical depth, at about elevation 720 before the hydraulic jump. Since the depth of this flow, and that of the tailwater were equal for all rates of discharge, it is evident that the velocities would increase in direct proportion to the discharge distortion ratio. This explains the fair correlation of the velocities at distances greater than fifty feet from the ogee base. However, at the higher distortions, the depth increases with the discharge, closer to the ogee, explaining the comparitively lower velocities (figure 22).

In order to check the theory, that the slope of the energy line increases with the square of the discharge, the following computations were made:

The value of Manning's n for the model was calculated using Manning's Equation, and the flow conditions of the undistorted test.

$$n = \frac{1.49}{Q} A R^{2/3} S^{1/2}$$

$$= \frac{1.49}{1.37} \times 2.09 \times (0.33)^{2/3} \times (0.00022)^{1/2}$$

$$= 0.016$$

Using this value of n in Manning's Equation, the theoretical energy line slopes were calculated for the other discharges. These slopes, along with the actual slopes measured, are shown in the following table

Discharge Distortion Ratio	Theoretical Slope	Actual Slope*
1.00	0.00022	0.00022
1.25	0.00034	0.00035
1.50	0.00049	0.00050
1.75	0.00067	0.00070

*Accuracy of measurement 0.001/40 = 0.00003

It can be seen from the table that the slopes actually measured in the tests were within the accuracy of measurement, of the slopes calculated by Manning's Equation.

The maximum change in depth, at the discharge distortion ratio of 1.75 was 0.018 feet. This was equal to five percent of the original depth of 0.36 feet. Therefore, a further increase of discharge distortion would not be recommended.

General conclusions on discharge distortion. Within the range tested, the discharge distortion did not appreciably change the flow patern, or change the velocity distribution, beyond the accuracy of measurement. Since the model contained a drop structure and the confluence of two channels, it can be assumed that the same result would have been obtained in a model with simpler flow conditions.

The Manning's Equation relationship, that the slope of the energy line varies with the square of the discharge, checked within the degree of accuracy of the measurements. It is therefore possible to make a slight change in the discharge ratio, in order to obtain verification of the water slopes, if the exact model roughness is not available.

CHAPTER VI

CONCLUSIONS

General conclusions on the various subjects discussed, have been given at the end of their respective chapters. A brief summary of those conclusions, obtained from the results of the tests, and from the literature, will be presented here.

Model distortion. Distortion should not be used in a moveable bed model, unless an economic study has shown that an undistorted model cannot be constructed at reasonable cost. If distortion is required, every effort should be made to minimize its effect, and special care should be taken in the verification and analysis of the model. Prototype performances to date, have proven the value of results obtained from distorted model studies.

Bed materials. The choice of a model bed material is usually an economic one. Light weight aggregates are in general considered only for small models, because of their relatively high cost. They are also more difficult to handle, and may tend to change their specific gravity under water.

The majority of moveable model studies are undertaken to compare erosion patterns caused by alternative hydraulic structures or arrangements. Tests have shown that the final stable depth and shape of scour is not a function of grain size. Therefore, the finest sand available, that will not ripple in the model, will be the cheapest bed material, and will require the shortest erosion time. Preliminary tests will indicate the necessary time scale for the study.

It is not normal practice to make quantitative estimates of scour from the results of model studies. However, if this type of study is to be attempted, it has been suggested that the ratio of the fall velocities of the bed materials should be chosen equal to the velocity scale ratio of the model. Verification of the model would be a prerequisite for a quantitative study.

Vertical distortion. More care and experience is required in the construction and operation of distorted models. Since the distortion magnifies secondary currents, the analysis of velocity and erosion patterns becomes more difficult, especially if the model contains complicated flow conditions, and channel junctions. Greater bed load movement and more disturbance of flow pattern is likely to occur in a vertically distorted model than in a slope distorted model, if they contain the same tractive force.

Structures in vertically distorted models should be constructed with their longitudinal horizontal scale identical to the vertical scale. If the method used to maintain the proper width of flow over the structure dictates distorted bays between piers, exaggerated side wall effect will result. Accurate measurements of discharge coefficients and flow profiles would then have to be taken on a larger undistorted model of the structure. Also, if the flow from the structure remains confined, the high velocity jet will appear to travel further downstream in a distorted model than in an undistorted model with the same vertical scale.

Discharge distortion. If a laboratory has sufficient pump capacity, discharge distortion can be the most economic and versatile method of distortion available. Tests can be run at the normal discharge to obtain flow patterns and water surface profiles, and for demonstrative purposes. The discharge can then be increased until sufficient tractive force is available for erosion studies. Tests have shown that the discharge ratio can be increased in models with complicated flow conditions, without measurably affecting the velocity distribution.

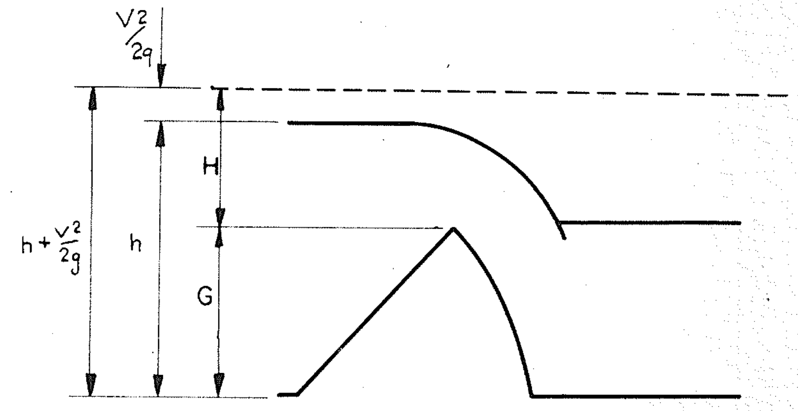
A slight change in discharge distortion can also be conveniently used to obtain the proper water surface slopes in verification tests, if the exact model roughness is not available.

APPENDIX A

VERTICAL DISTORTION TEST RESULTS

TEST No.	q	h	V	$V^2/2g$	$h + V^2/2g$	G	H	$H^{3/2}$	C
1-W	340[E]	45.0	7.55	0.88	45,9	24.0	21.9	102.0	3.33
1-P	340	45.5	7.48	0.87	46.4	25.0	21.4	98.5	3.45
2-W	314	41.5	7.57	0.89	42.4	21.2	21.2	98.0	3.20
2-P	314	41.5	7.57	0.89	42.2	22.0	20.4	92.0	3.41
3-W	136	21.0	6.48	0.65	21.7	8.2	13.5	49.5	2.65
3-P	136	21.4	6.35	0.63	22.0	8.9	13.1	47.3	2.88
4-W	212	38.8	5.47	0.47	39.3	24.7	14.6	56.0	3.79
4-P	212	39.3	5.40	0.45	39.8	25.6	14.2	51.6	4.10
5-W	165.7	33.7	4.91	0.37	34.1	20.7	13.4	49.0	3.38
5-P	165.7	34.1	4.85	0.37	34.5	22.5	12.0	41.7	3.97
6-W	306.5[E]	48.8	6.30	0.62	49.4	29.5	19.9	89.0	3.45
6-P	306.5	49.3	6.23	0.60	49.9	30.7	19.2	84.0	3.65
7-W	150	25.7	5.84	0.53	26.2	13.2	12.2	44.2	3.39
7-P	150	26.3	5.70	0.50	26.8	14.4	11.9	41.0	3.66

$q = CH^{3/2}$



CALCULATIONS OF "C" FOR DIFFERENT TESTS

1 - W = TEST No. 1 - WOODEN MODEL

1 - P = TEST No. 1 - PLEXIGLASS MODEL

Figure 4

GATE HEIGHT VS DISCHARGE

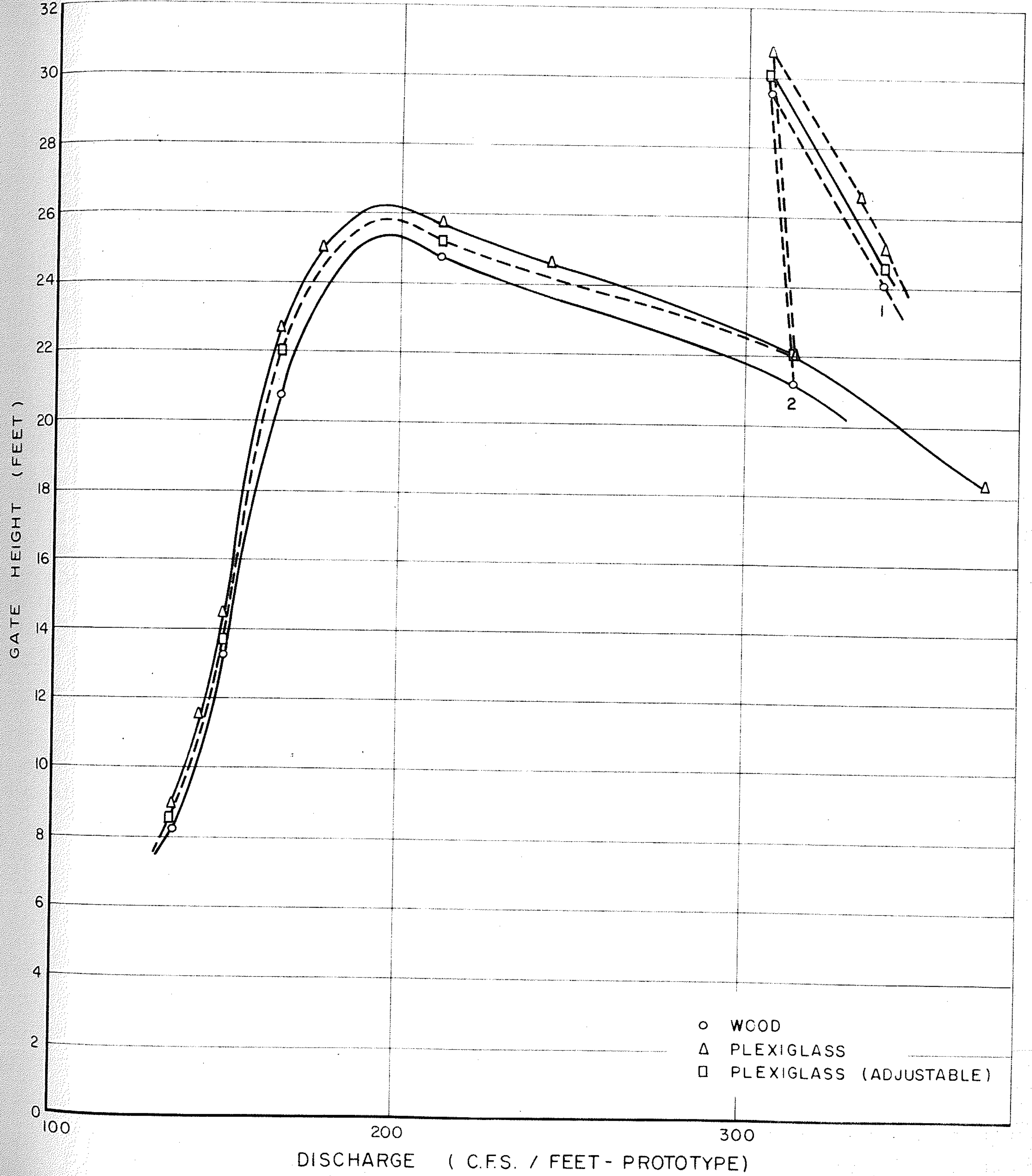


Figure 5

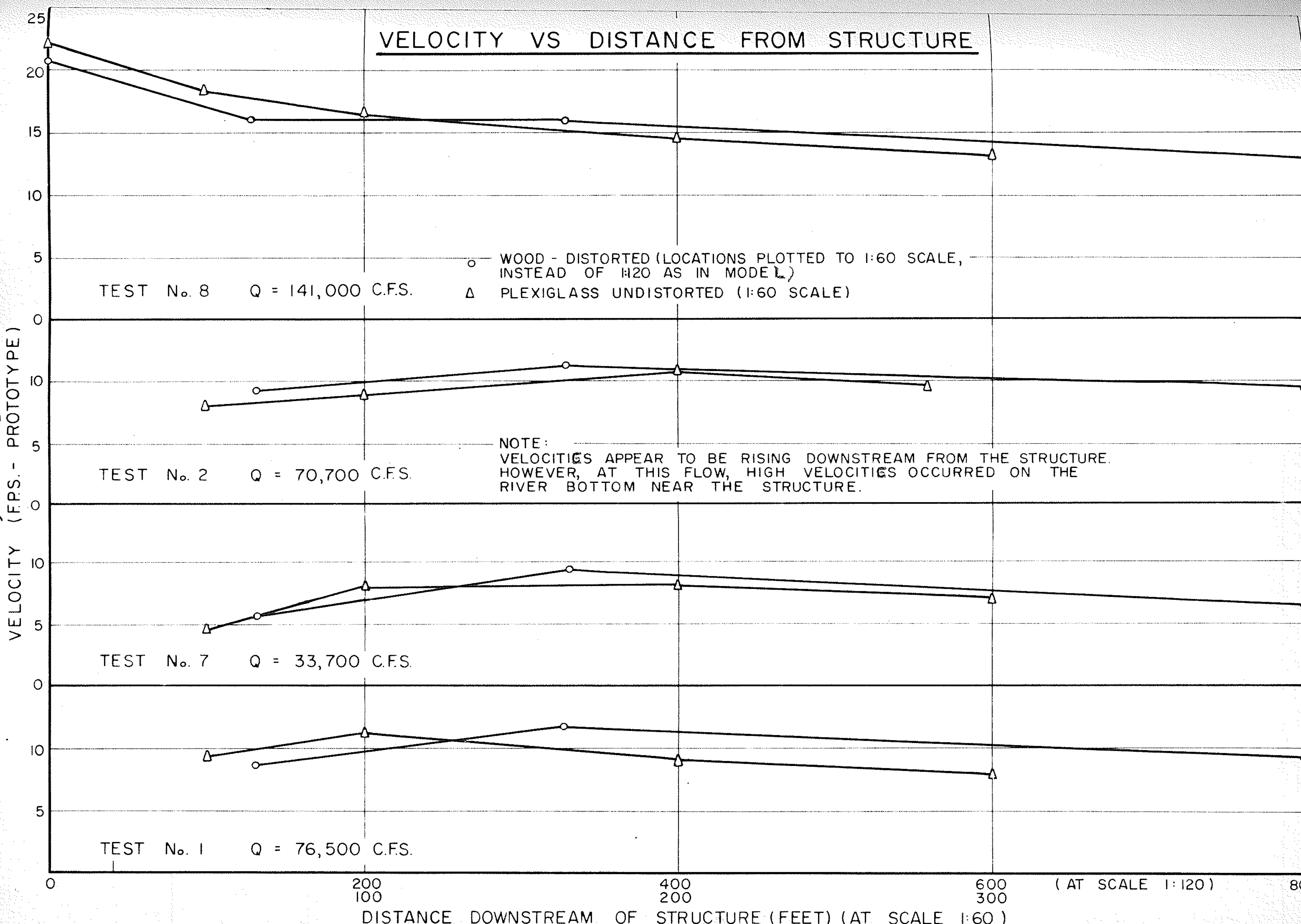

VELOCITY VS DISTANCE FROM STRUCTURE
WOOD - DISTORTED (LOCATIONS PLOTTED TO 1:60 SCALE, INSTEAD OF 1:120 AS IN MODEL)
PLEXIGLASS UNDISTORTED (1:60 SCALE)
TEST No. 8 Q = 141,000 C.F.S.
TEST No. 2 Q = 70,700 C.F.S.
NOTE:
VELOCITIES APPEAR TO BE RISING DOWNSTREAM FROM THE STRUCTURE. HOWEVER, AT THIS FLOW, HIGH VELOCITIES OCCURRED ON THE RIVER BOTTOM NEAR THE STRUCTURE.
TEST No. 7 Q = 33,700 C.F.S.
TEST No. 1 Q = 76,500 C.F.S.
VELOCITY (F.P.S. - PROTOTYPE)
DISTANCE DOWNSTREAM OF STRUCTURE (FEET) (AT SCALE 1:60)
(AT SCALE 1:120)
0
200
100
400
200
600
300
800
25
20
15
10
5
0

Figure 6

TEST No. 1

FIGURE 1

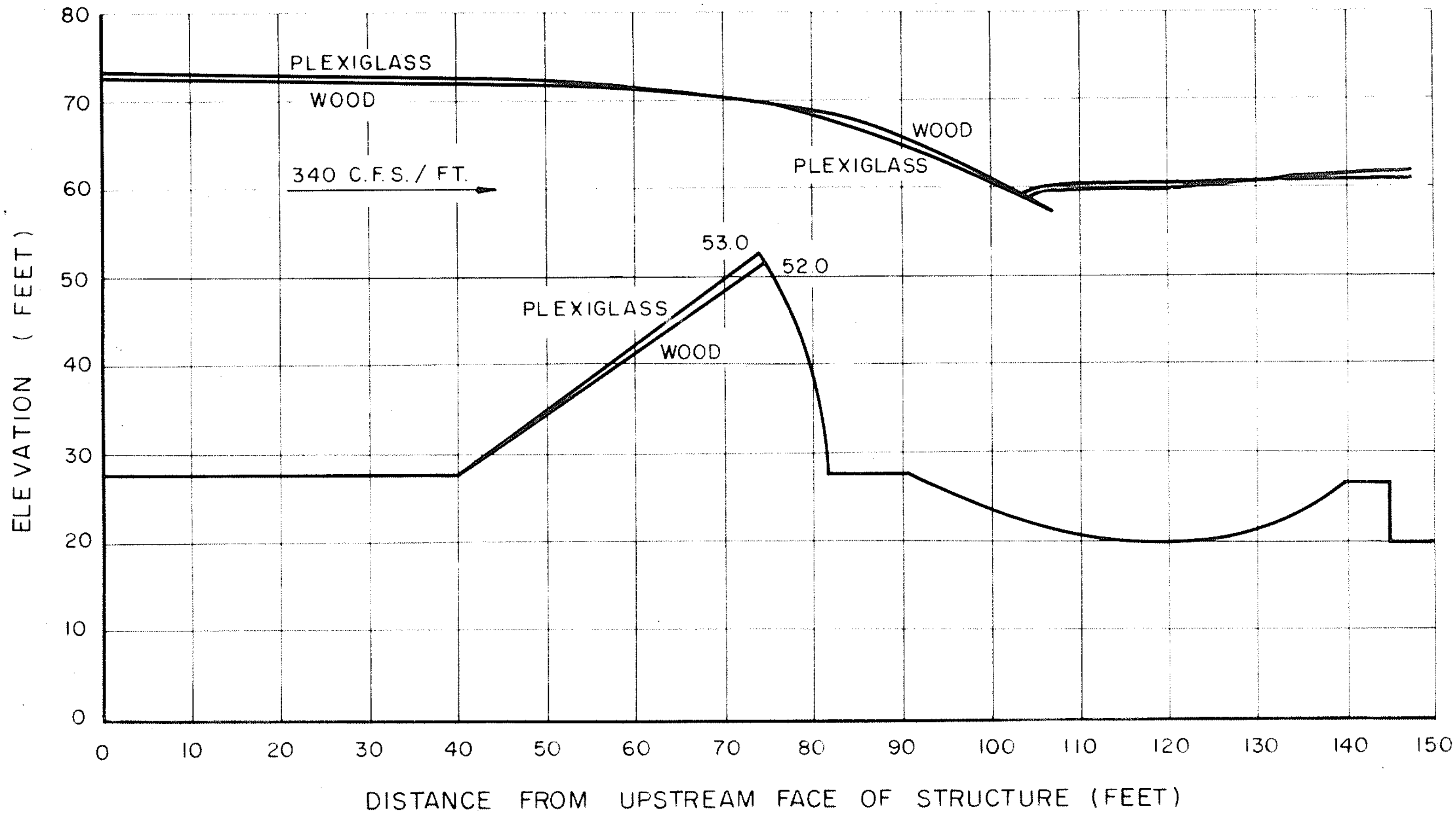


Figure 7

TEST No. 2

FIGURE 2

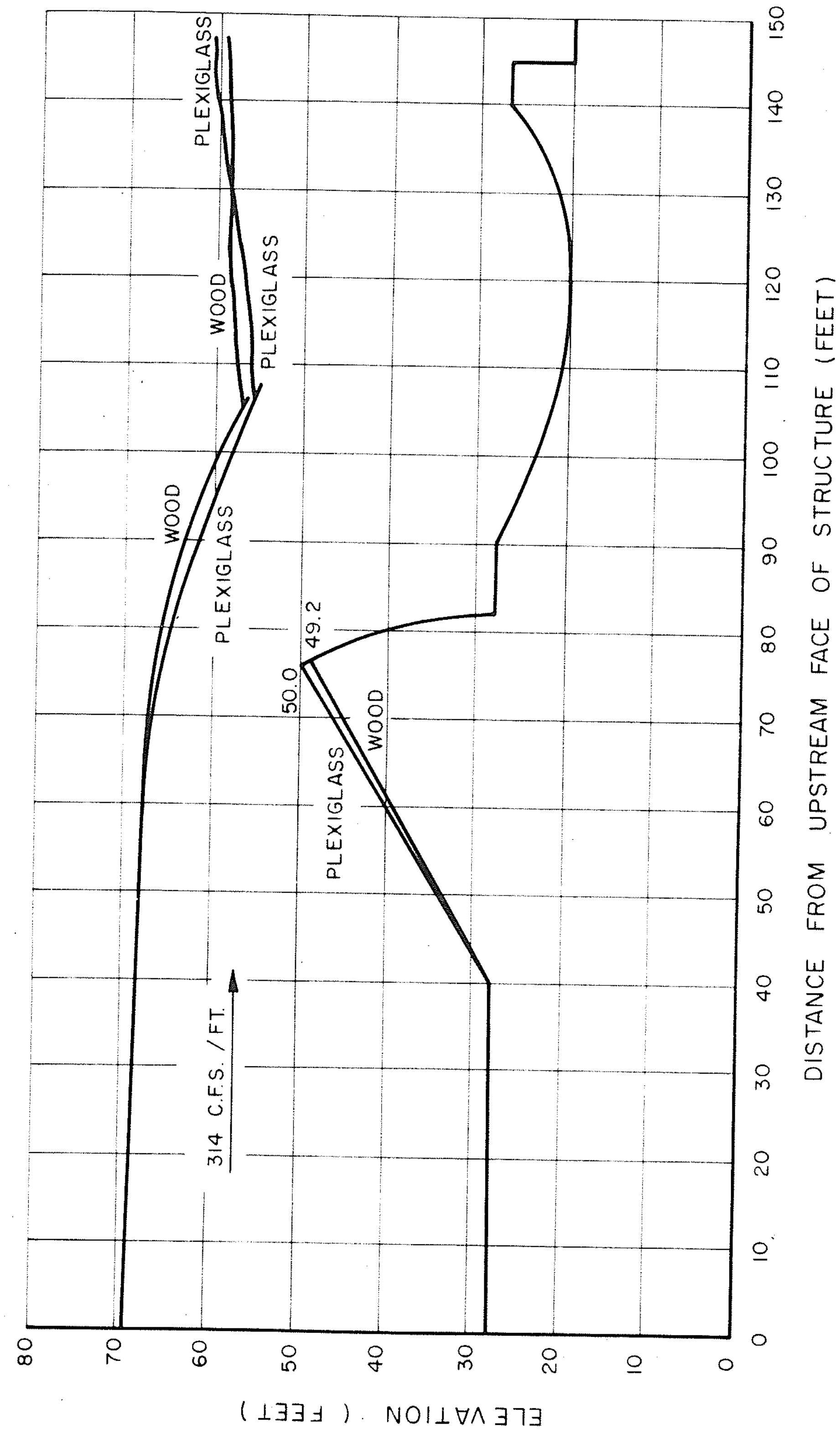


Figure 8

TEST No. 3

FIGURE 3

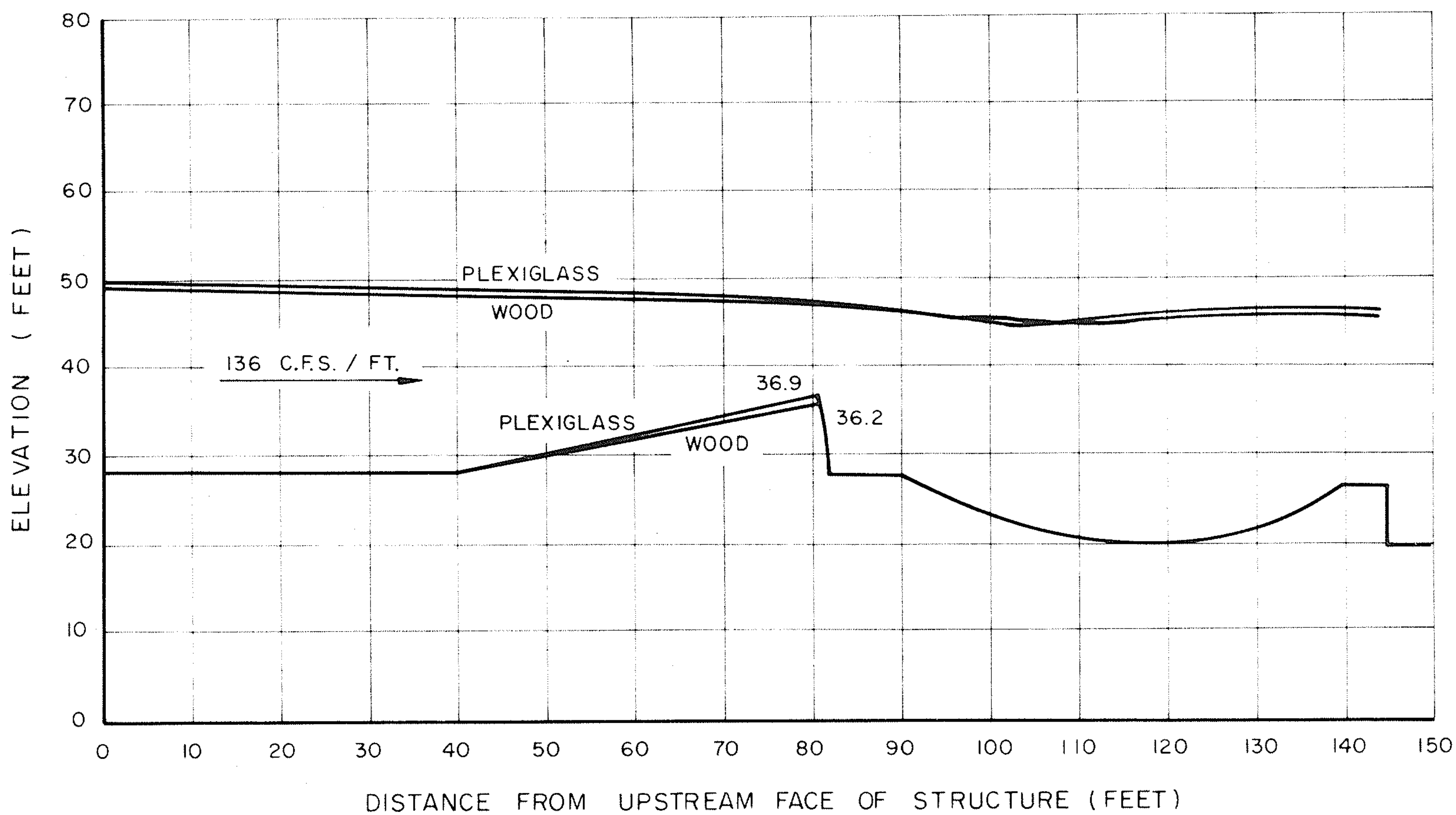


Figure 9

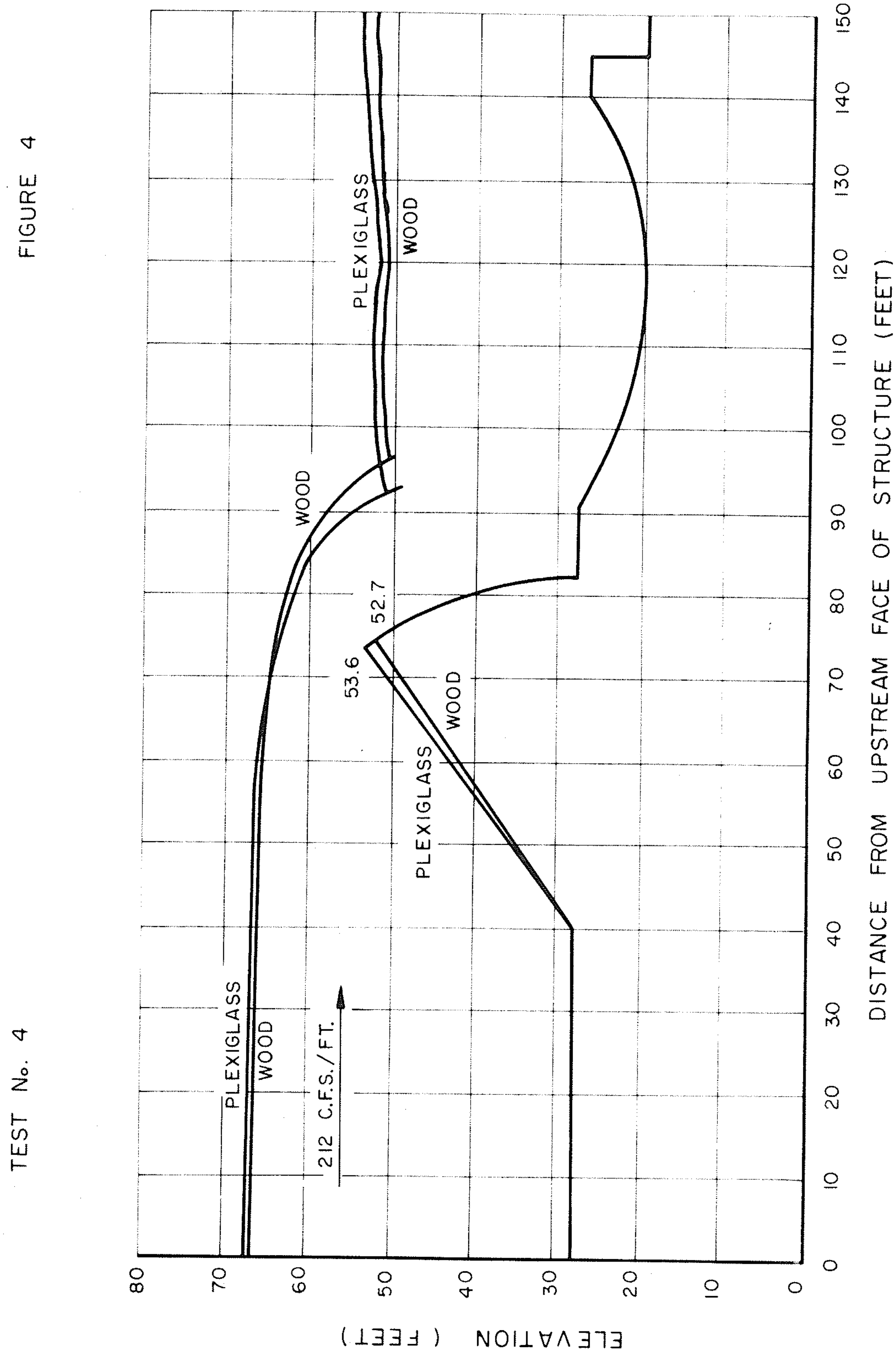

TEST No. 4
FIGURE 4
PLEXIGLASS
WOOD
212 C.F.S./FT.
PLEXIGLASS
WOOD
53.6
52.7
WOOD
PLEXIGLASS
WOOD
ELEVATION (FEET)
0
10
20
30
40
50
60
70
80
DISTANCE FROM UPSTREAM FACE OF STRUCTURE (FEET)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150

Figure 10

TEST No. 5

FIGURE 5

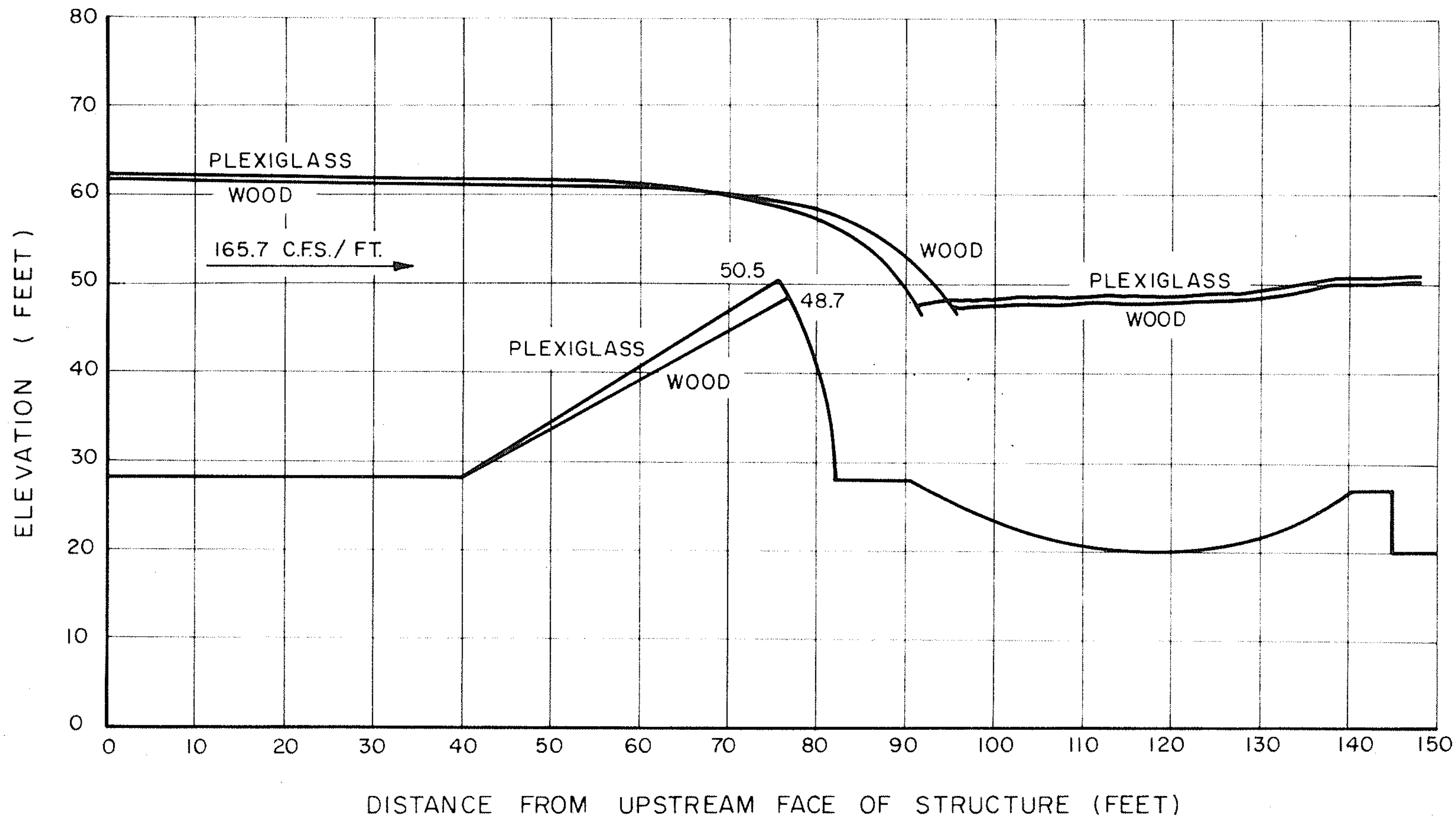


Figure 11

TEST No. 6

FIGURE 6

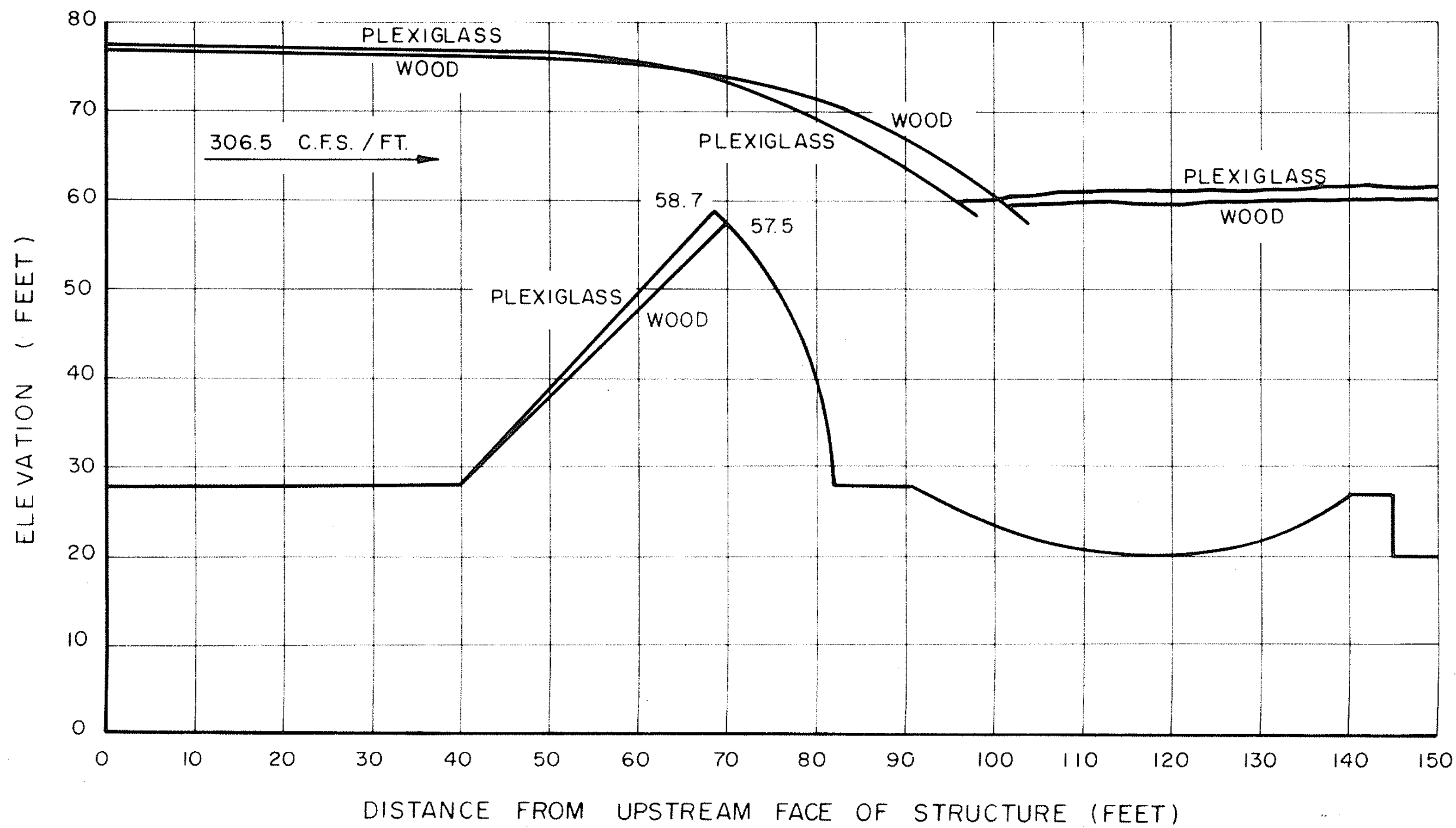


Figure 12

TEST No. 7

FIGURE 7

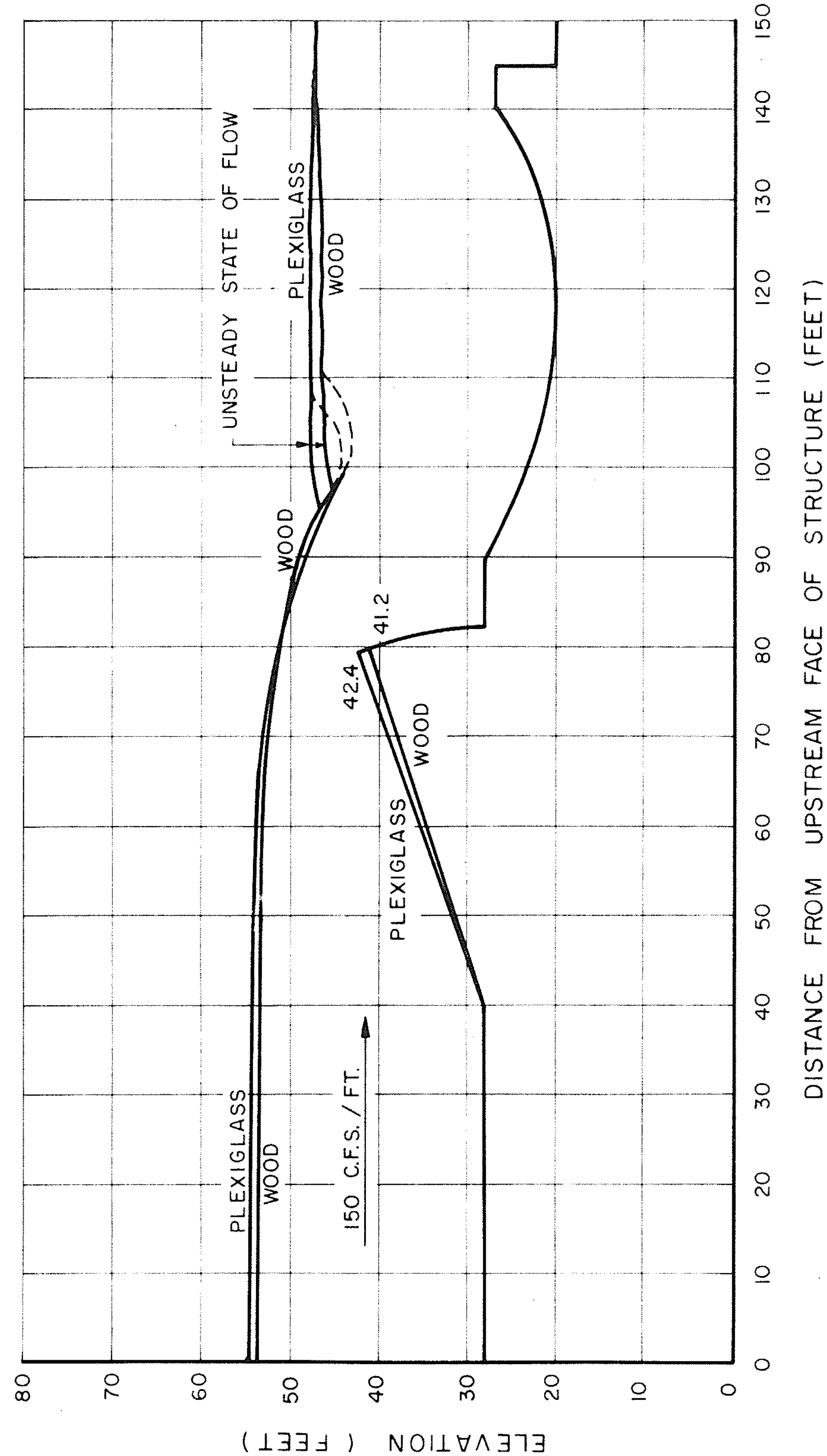


Figure 13

APPENDIX B

DISCHARGE DISTORTION TEST RESULTS

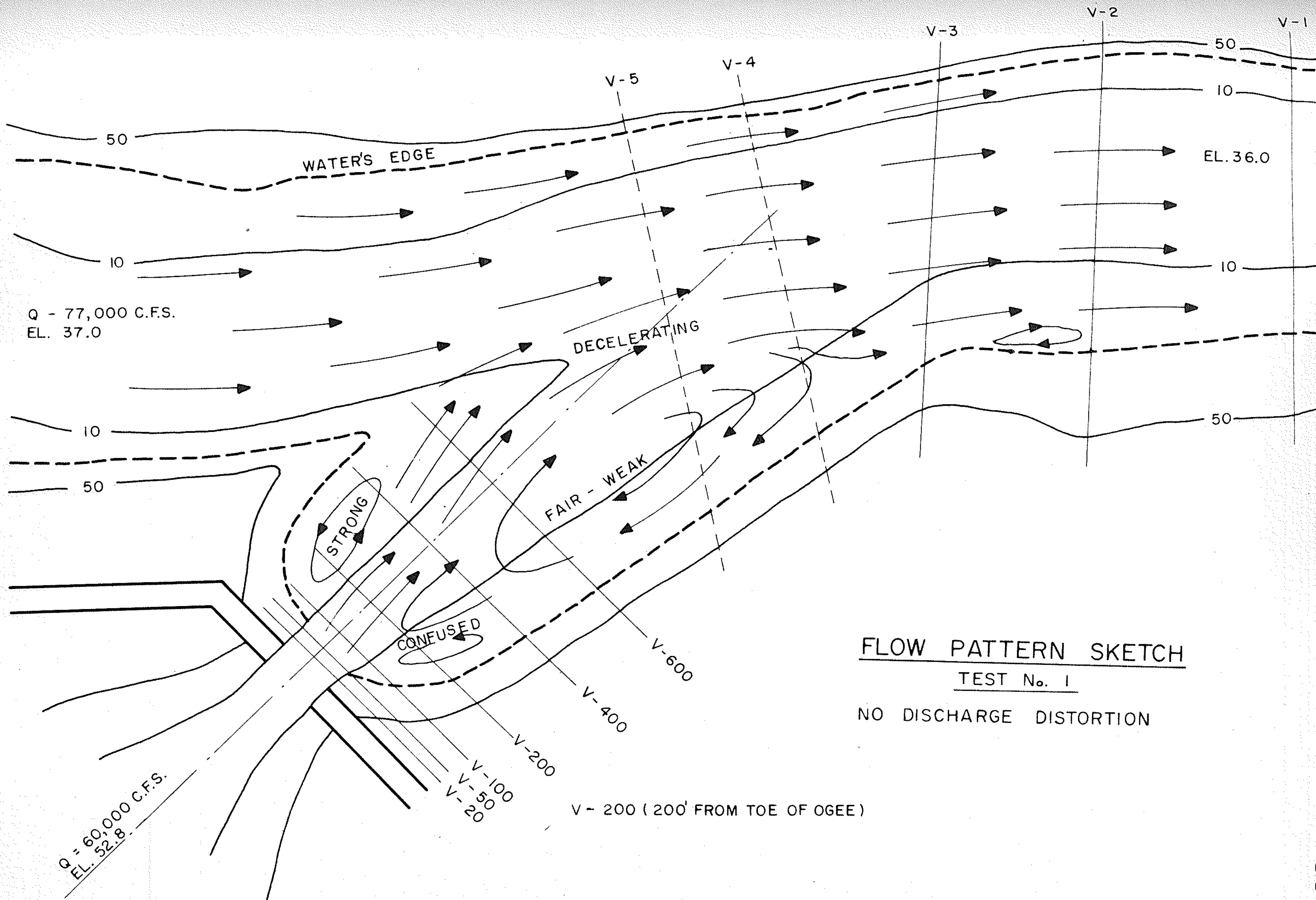

FLOW PATTERN SKETCH
TEST No. 1
NO DISCHARGE DISTORTION
V - 200 (200' FROM TOE OF OGEE)
Q - 77,000 C.F.S.
EL. 37.0
Q = 60,000 C.F.S.
EL. 52.8
EL. 36.0
WATER'S EDGE
DECELERATING
FAIR - WEAK
STRONG
CONFUSED
V-1
V-2
V-3
V-4
V-5
V-600
V-400
V-200
V-100
V-50
V-20
50
10

Figure 14

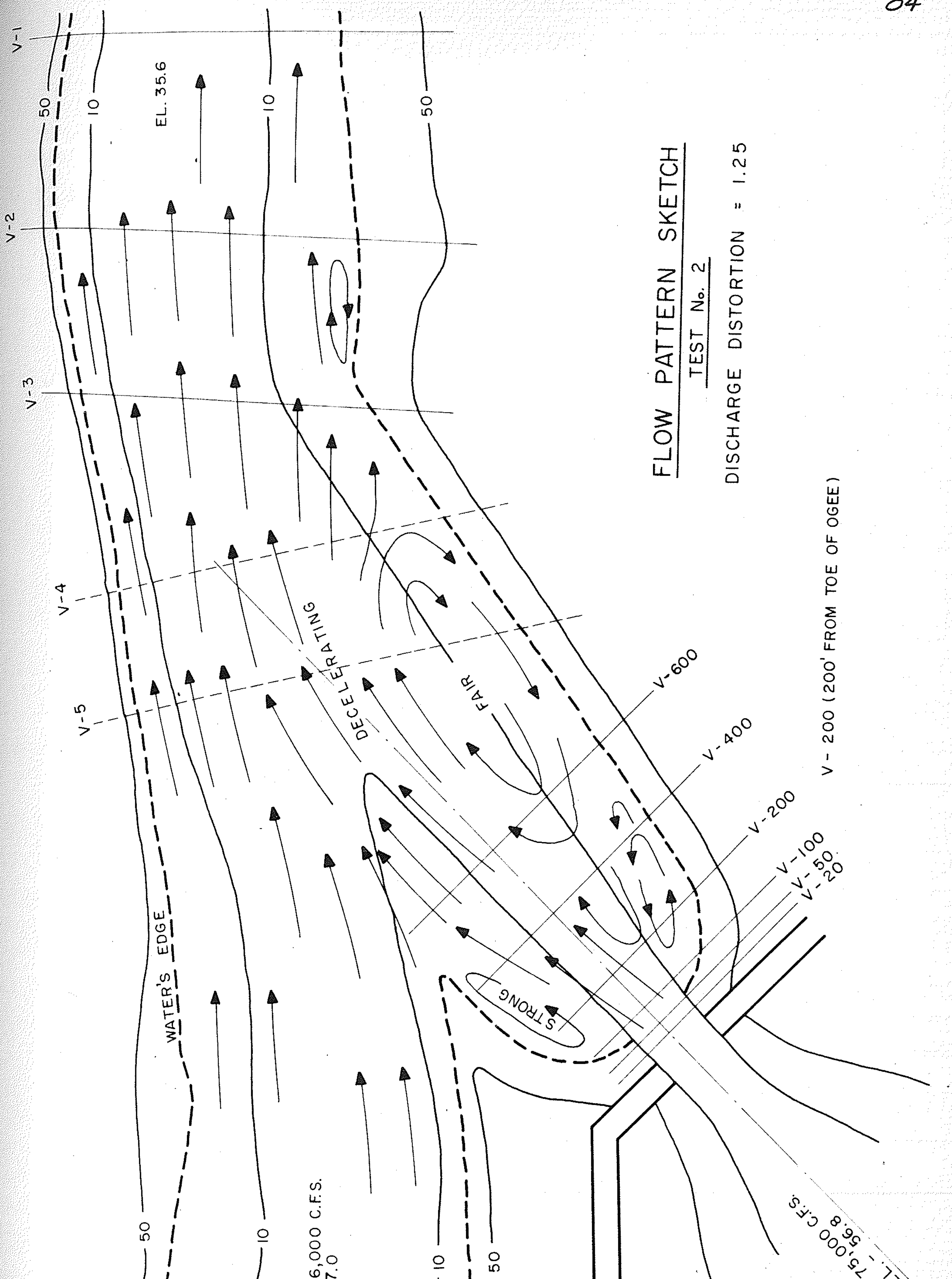

FLOW PATTERN SKETCH
TEST No. 2
DISCHARGE DISTORTION = 1.25
V - 200 (200' FROM TOE OF OGEE)
V-1
V-2
V-3
V-4
V-5
V-600
V-400
V-200
V-100
V-50
V-20
EL. 35.6
50
10
DECELERATING
FAIR
STRONG
WATER'S EDGE
Q - 96,000 C.F.S.
EL. 37.0
Q = 75,000 C.F.S.
EL. - 56.8

Figure 15

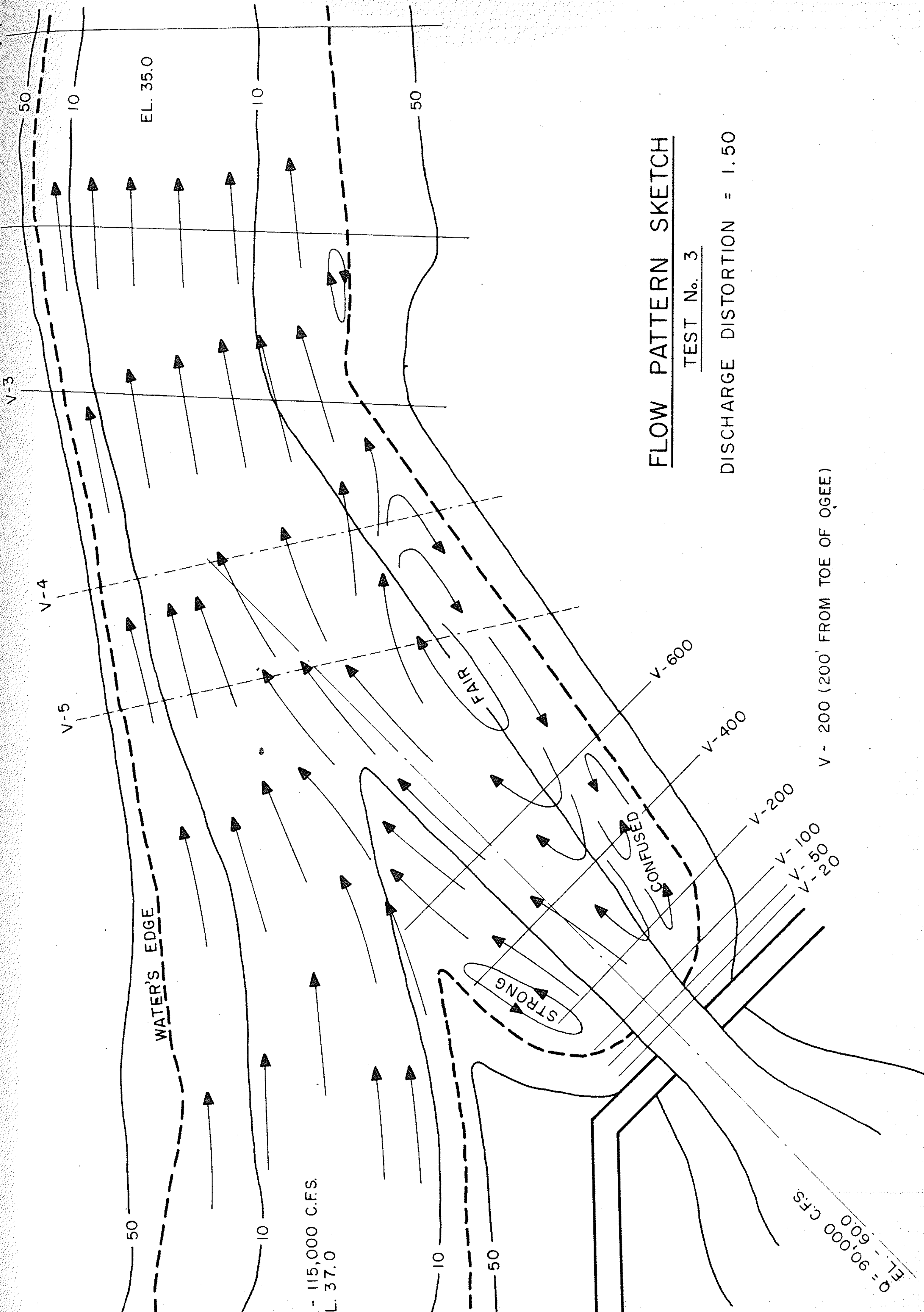
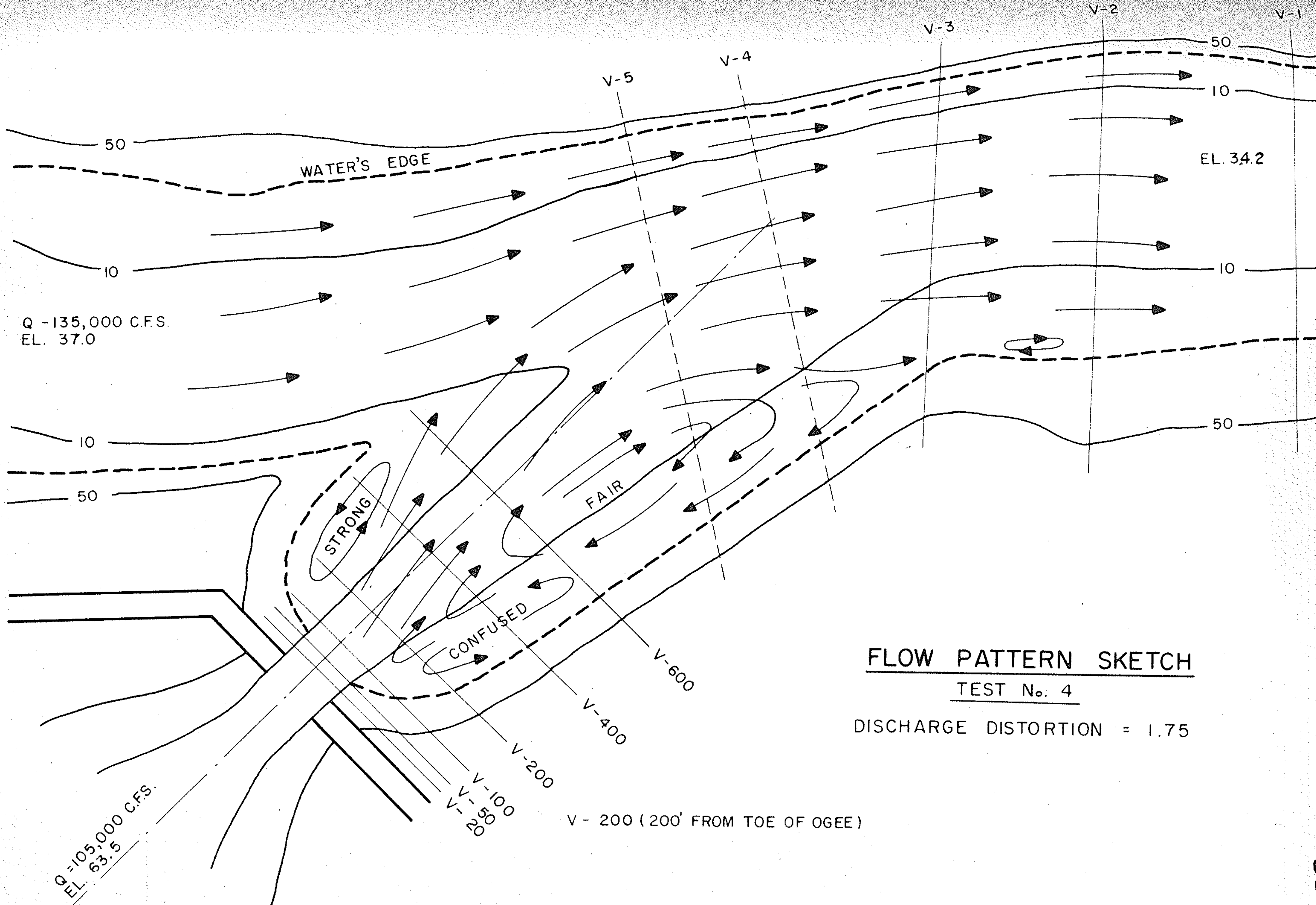

FLOW PATTERN SKETCH
TEST No. 3
DISCHARGE DISTORTION = 1.50
V - 200 (200' FROM TOE OF OGEE)
EL. 35.0
Q - 115,000 C.F.S.
EL. 37.0
Q = 90,000 C.F.S.
EL. - 60.0
WATER'S EDGE
FAIR
CONFUSED
STRONG
V-1
V-2
V-3
V-4
V-5
V-600
V-400
V-200
V-100
V-50
V-20
50
10
10
50
50
10
10
50

Figure 16



FLOW PATTERN SKETCH

TEST No. 4

DISCHARGE DISTORTION = 1.75

Figure 17

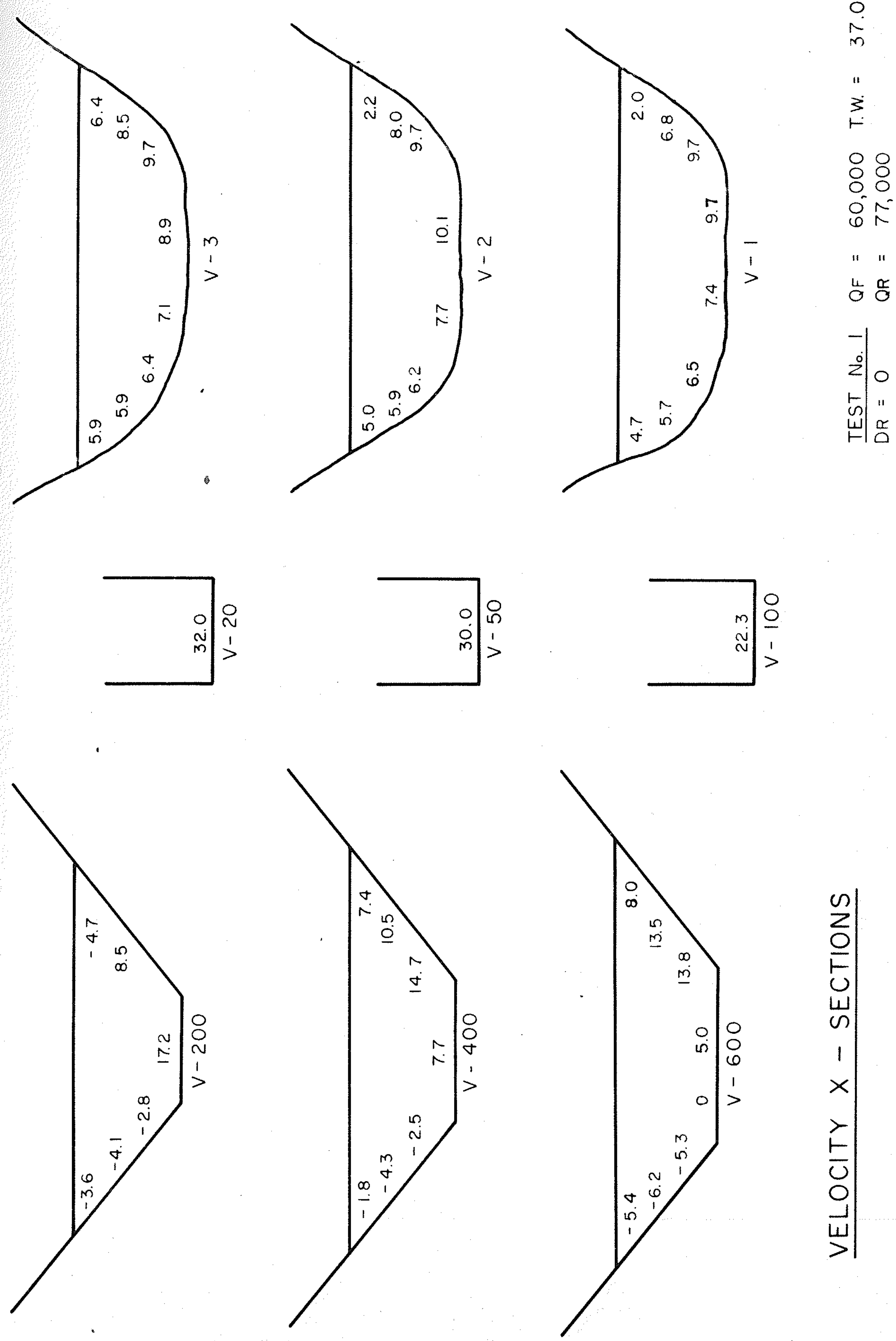
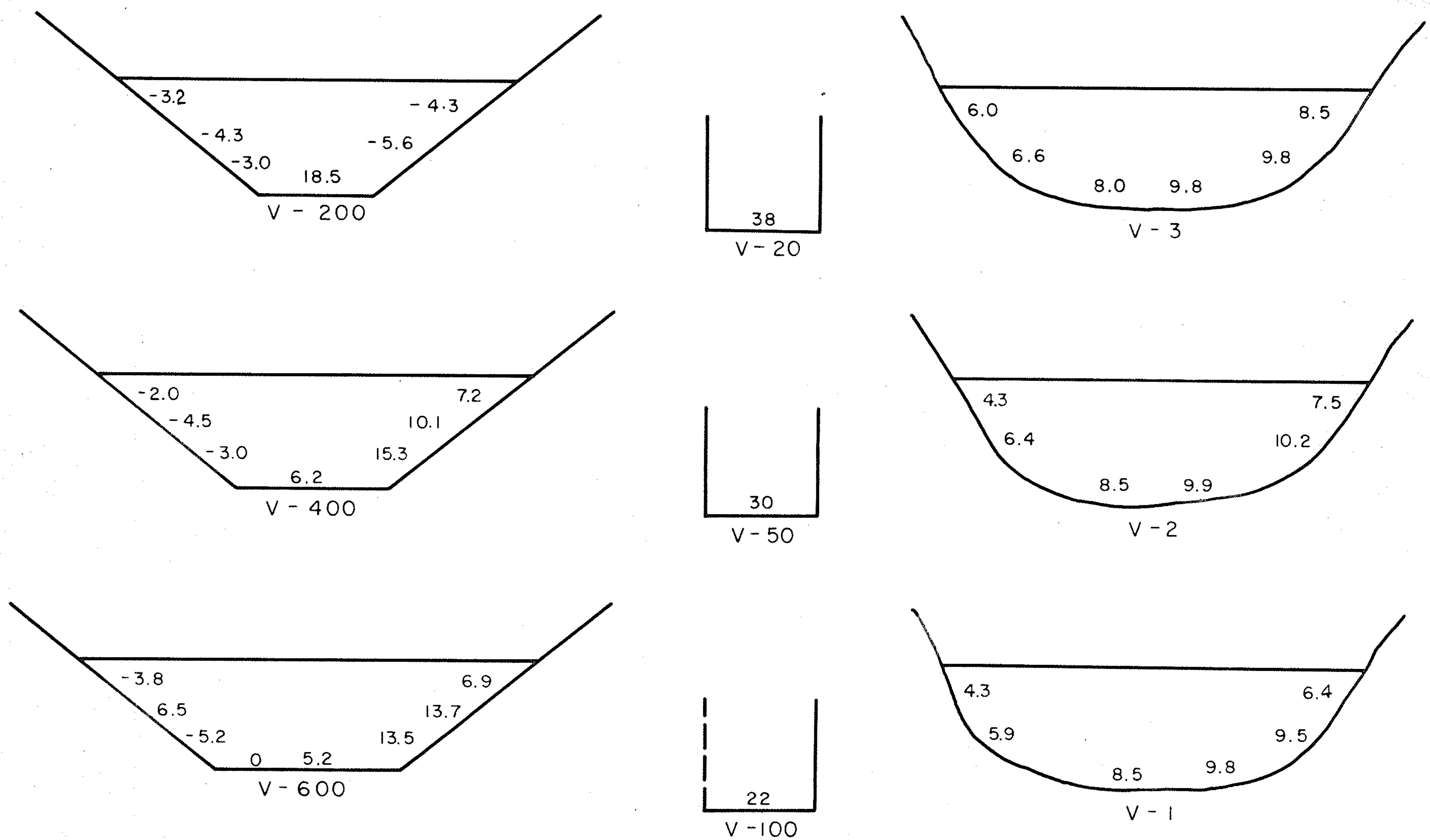

5.9
5.9
6.4
7.1
8.9
9.7
8.5
6.4
V - 3
5.0
5.9
6.2
7.7
10.1
9.7
8.0
2.2
V - 2
4.7
5.7
6.5
7.4
9.7
9.7
6.8
2.0
V - 1
32.0
V - 20
30.0
V - 50
22.3
V - 100
-3.6
-4.1
-2.8
17.2
8.5
-4.7
V - 200
-1.8
-4.3
-2.5
7.7
14.7
10.5
7.4
V - 400
-5.4
-6.2
-5.3
0
5.0
13.8
13.5
8.0
V - 600
VELOCITY X - SECTIONS
TEST No. 1 QF = 60,000 T.W. = 37.0
DR = 0 QR = 77,000

Figure 18



VELOCITY X - SECTIONS

TEST No. 2 QF = 75,000 T.W. = 37.0
DR = 1.25 QR = 96,000

Figure 19

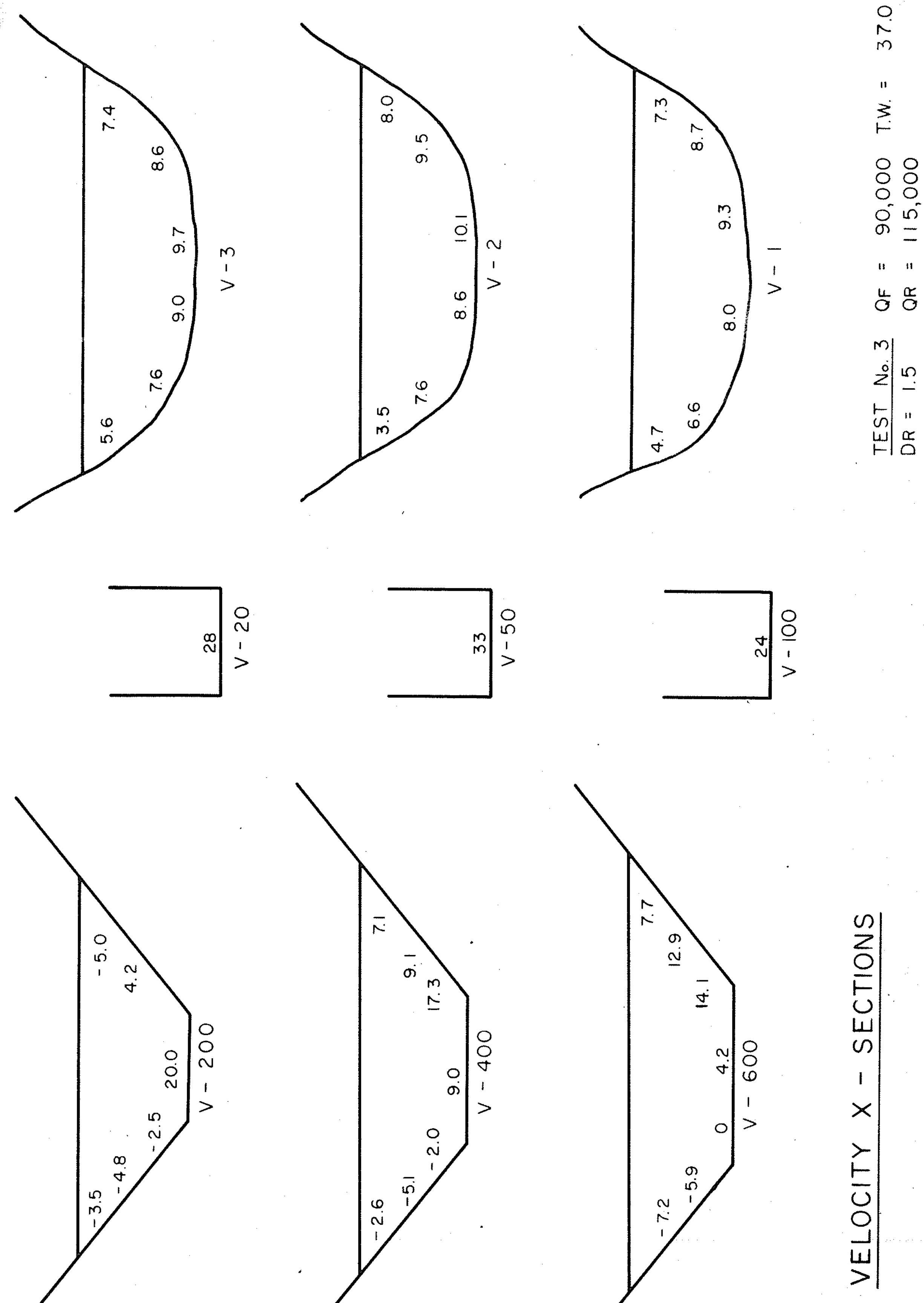
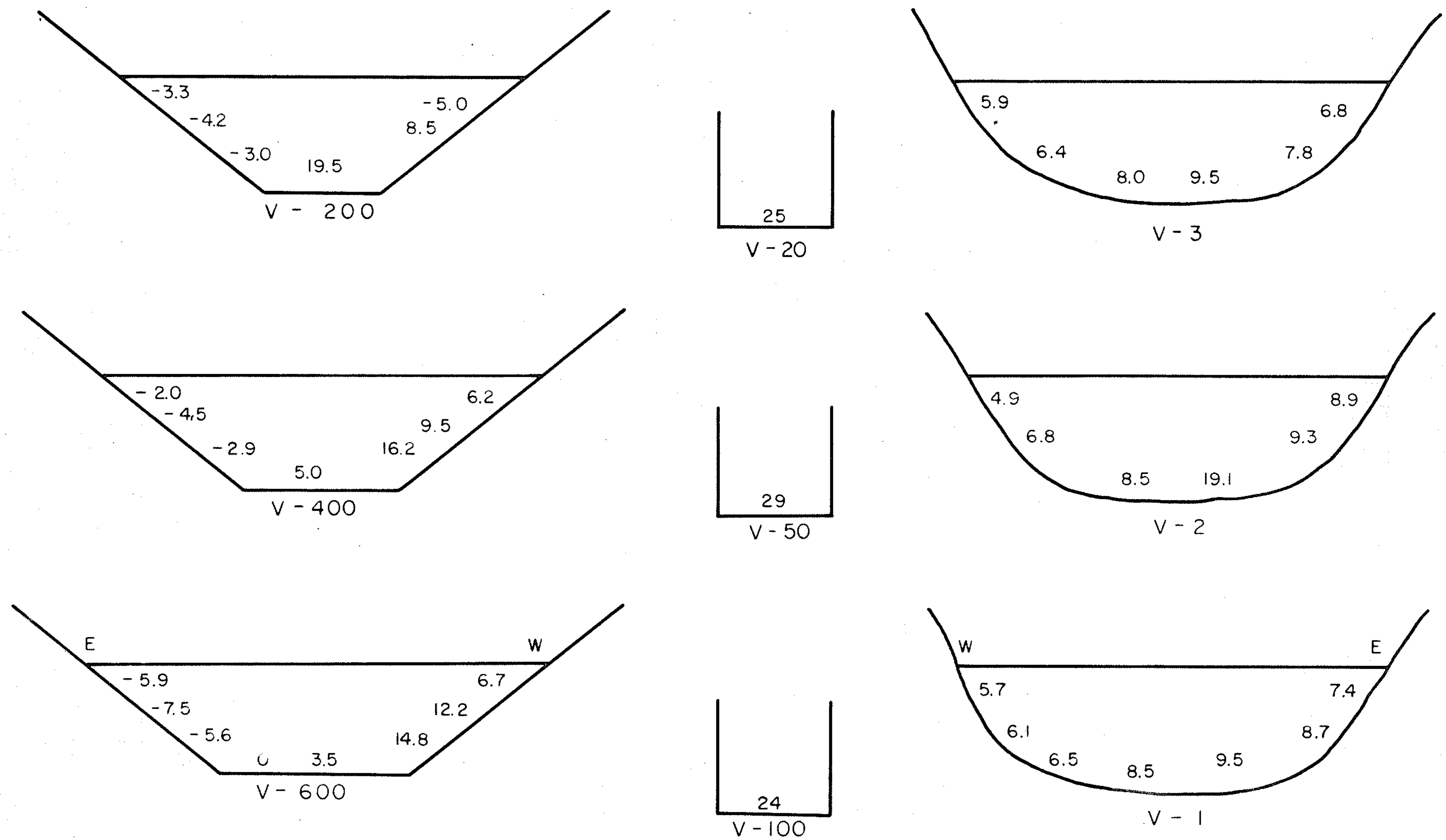

VELOCITY X - SECTIONS
TEST No. 3
QF = 90,000
T.W. = 37.0
DR = 1.5
QR = 115,000
V - 3
5.6
7.6
9.0
9.7
8.6
7.4
V - 2
3.5
7.6
8.6
10.1
9.5
8.0
V - 1
4.7
6.6
8.0
9.3
8.7
7.3
V - 20
28
V - 50
33
V - 100
24
V - 200
-3.5
-4.8
-2.5
20.0
4.2
-5.0
V - 400
-2.6
-5.1
-2.0
9.0
17.3
9.1
7.1
V - 600
-7.2
-5.9
0
4.2
14.1
12.9
7.7

Figure 20



VELOCITY X - SECTIONS

TEST No. 4 QF = 105,000 T.W. = 37.0
DR = 1.75 QR = 135,000

Figure 21

CENTRE LINE VELOCITIES

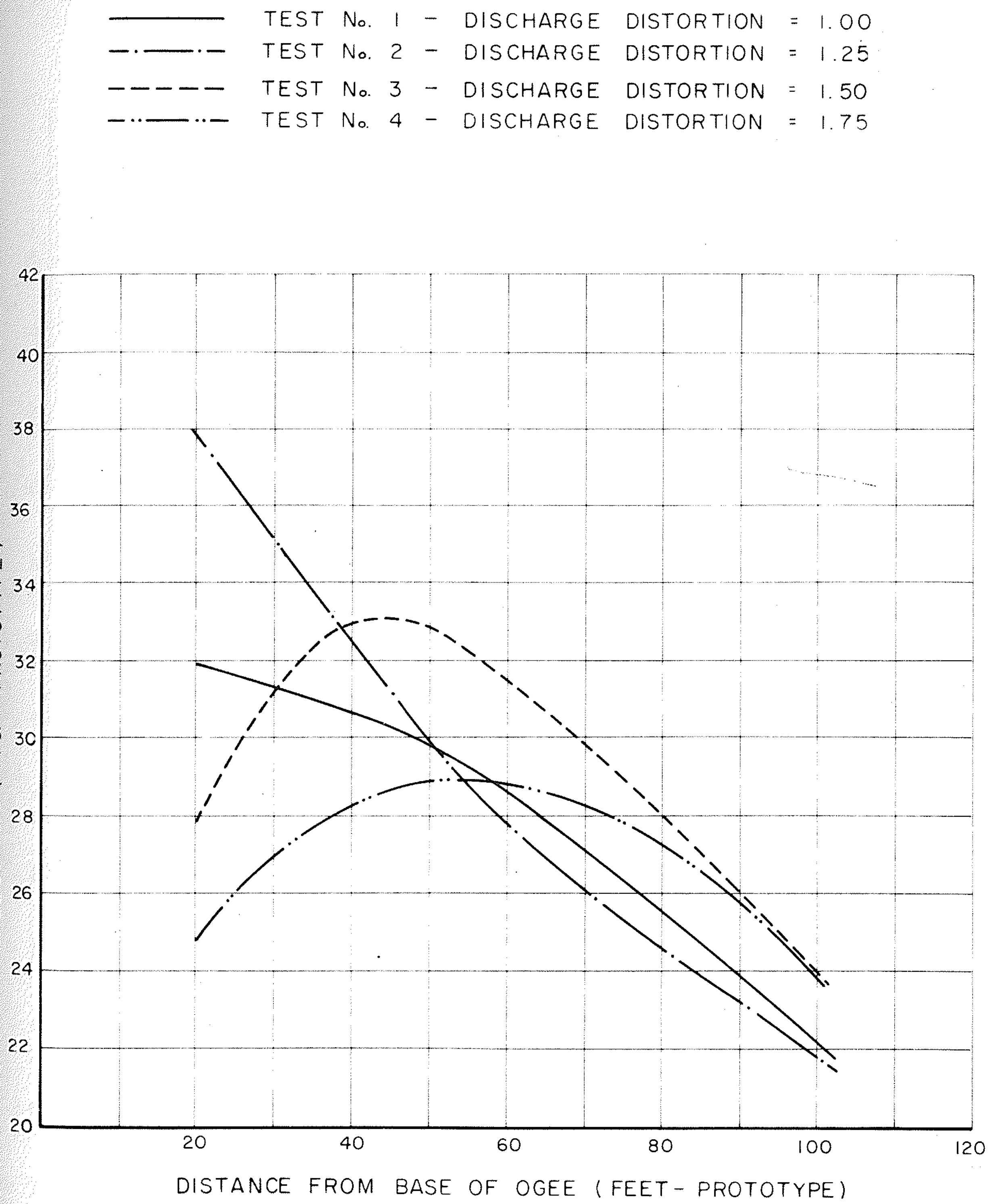


Figure 22

VELOCITY PROFILES AT CROSS-SECTION V-200

———	TEST No. 1 – DISCHARGE DISTORTION = 1.00
—·—·—	TEST No. 2 – DISCHARGE DISTORTION = 1.25
– – – –	TEST No. 3 – DISCHARGE DISTORTION = 1.50
—··—··—	TEST No. 4 – DISCHARGE DISTORTION = 1.75

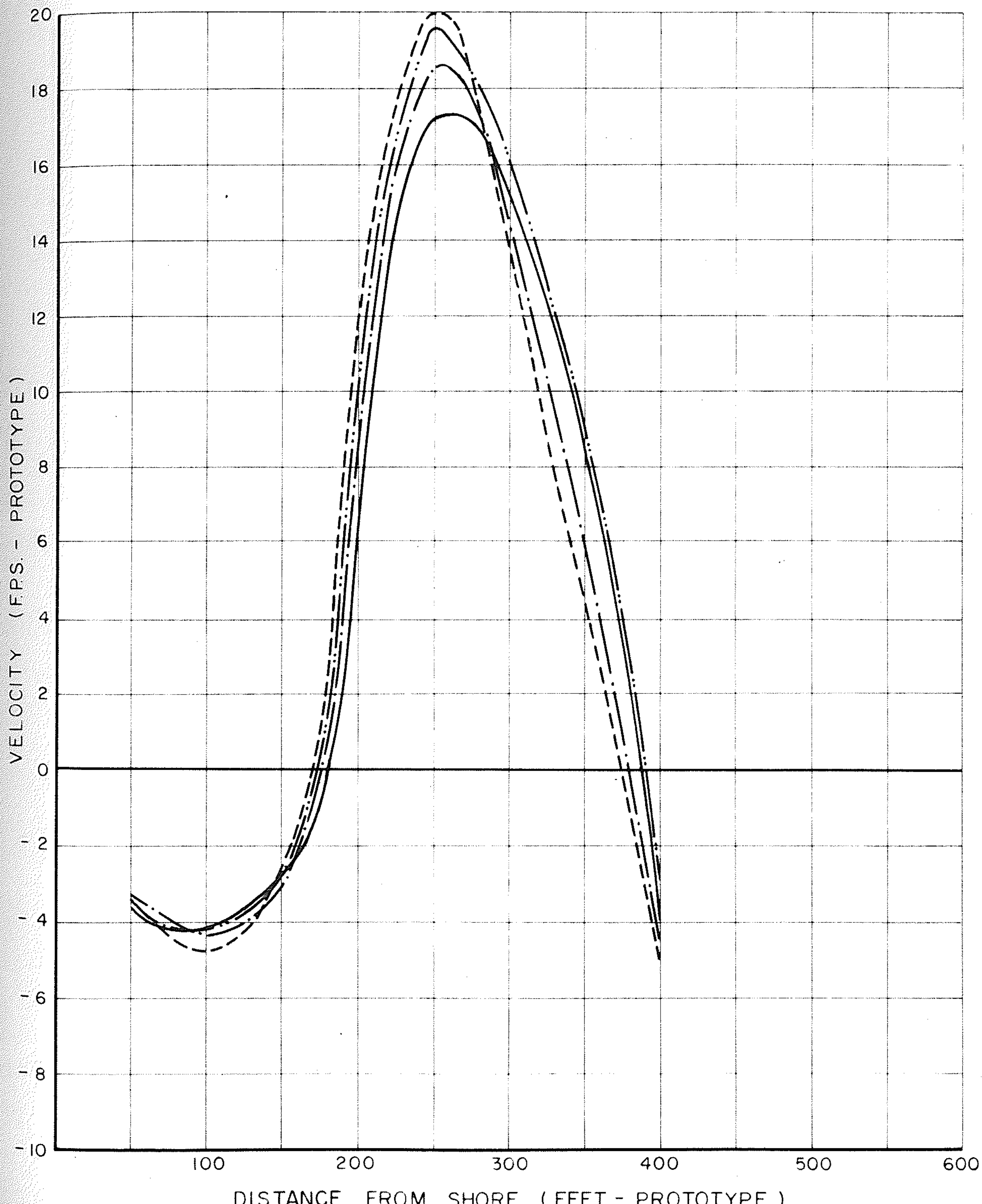


Figure 23

VELOCITY PROFILES AT CROSS-SECTION V-400

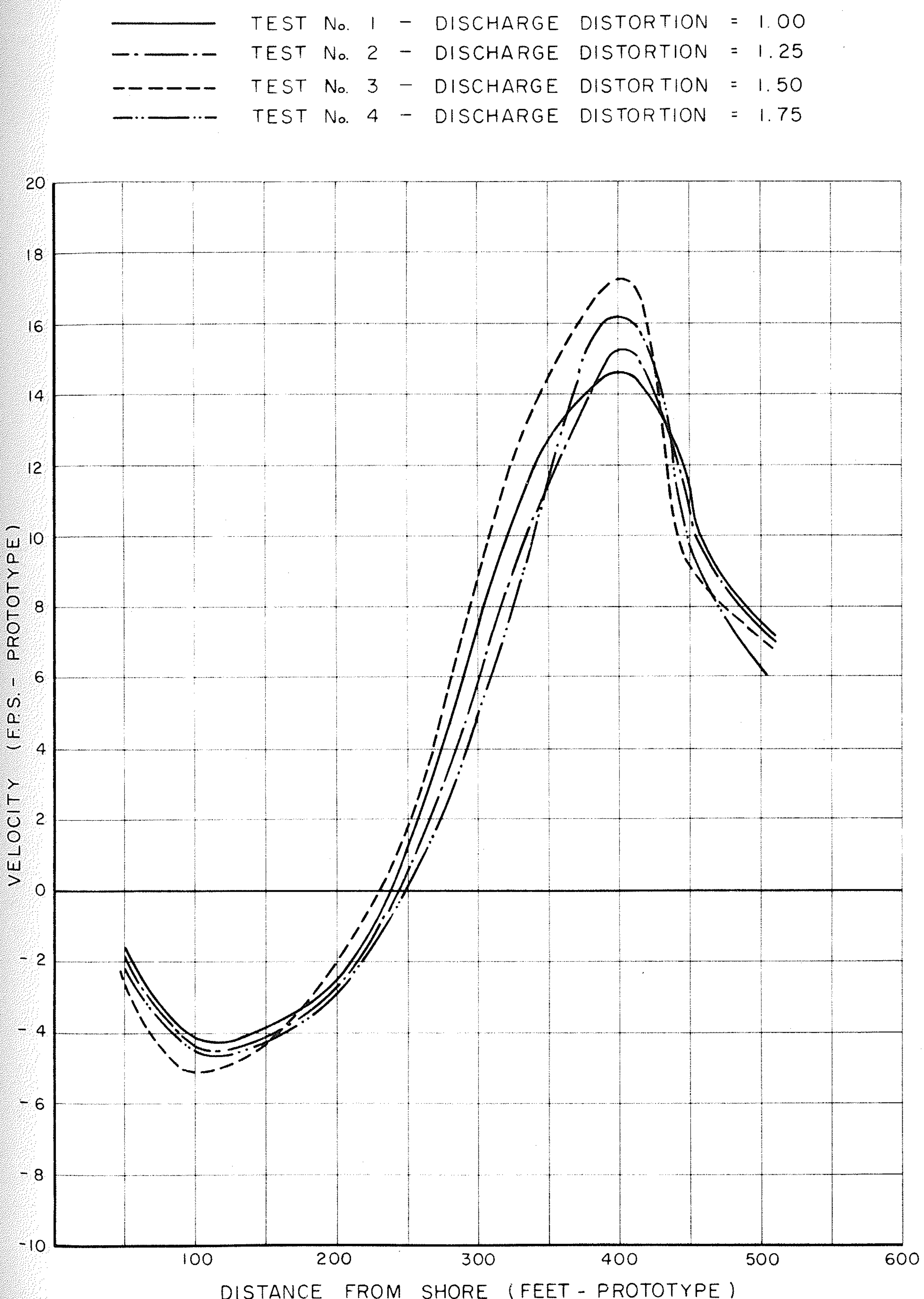


Figure 24

VELOCITY PROFILES AT CROSS - SECTION V-600

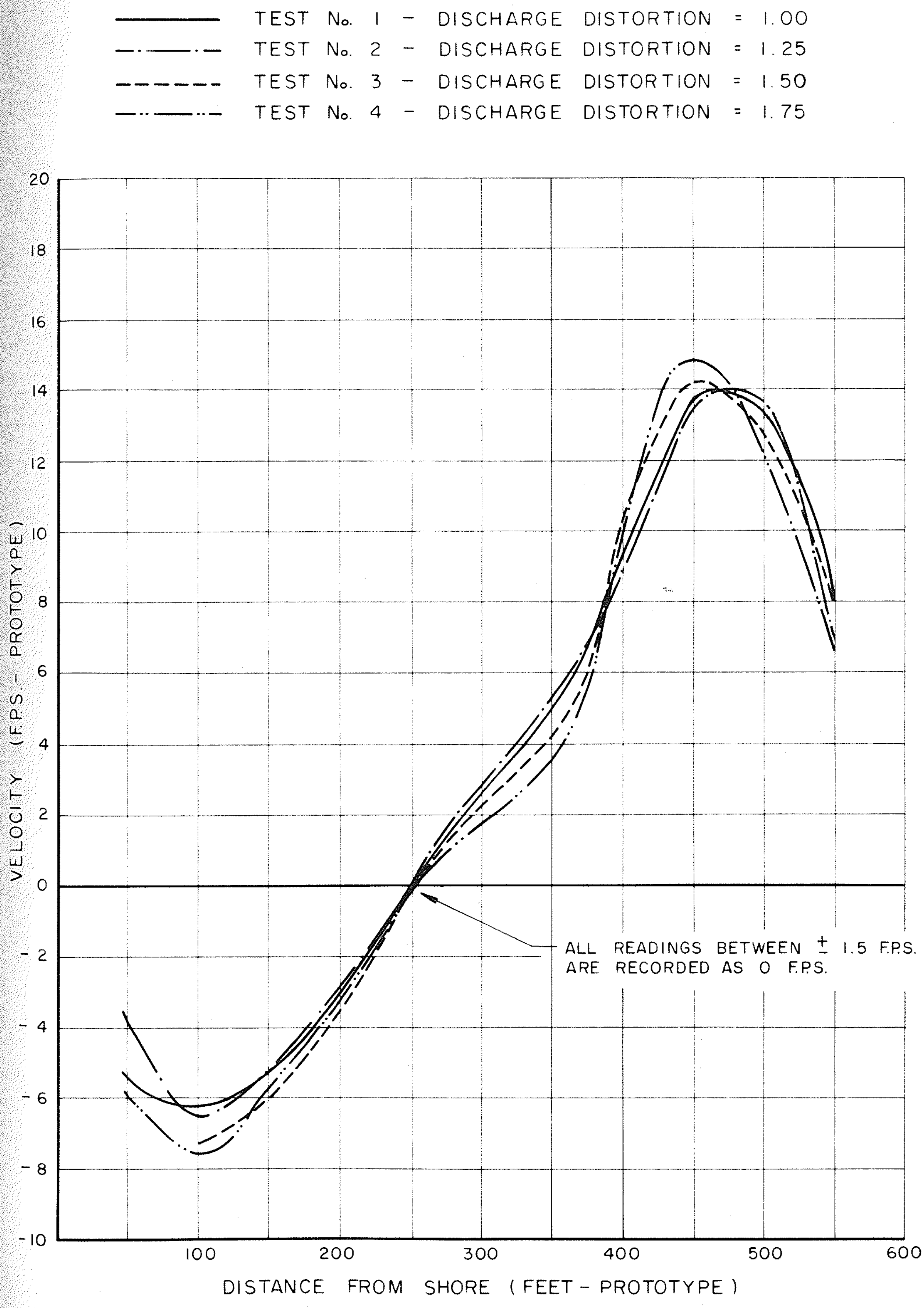


Figure 25

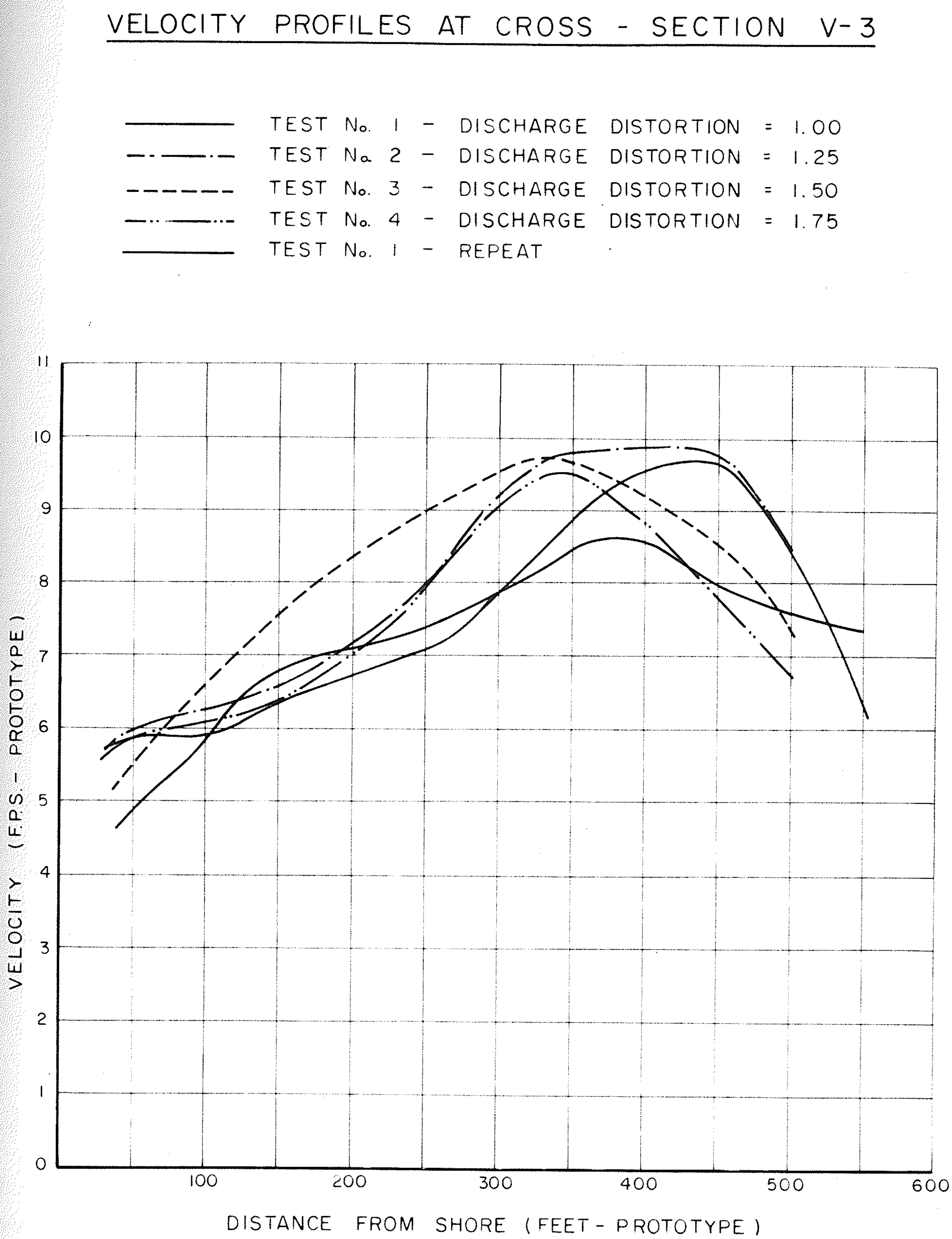

VELOCITY PROFILES AT CROSS - SECTION V-3
TEST No. 1 - DISCHARGE DISTORTION = 1.00
TEST No. 2 - DISCHARGE DISTORTION = 1.25
TEST No. 3 - DISCHARGE DISTORTION = 1.50
TEST No. 4 - DISCHARGE DISTORTION = 1.75
TEST No. 1 - REPEAT
VELOCITY (F.P.S. - PROTOTYPE)
0
1
2
3
4
5
6
7
8
9
10
11
100
200
300
400
500
600
DISTANCE FROM SHORE (FEET - PROTOTYPE)

Figure 26

VELOCITY PROFILES AT CROSS - SECTION V-2

————————	TEST No. 1 - DISCHARGE DISTORTION = 1.00
—·——·—	TEST No. 2 - DISCHARGE DISTORTION = 1.25
— — — — —	TEST No. 3 - DISCHARGE DISTORTION = 1.50
—··——··—	TEST No. 4 - DISCHARGE DISTORTION = 1.75
————————	TEST No. 1 - REPEAT

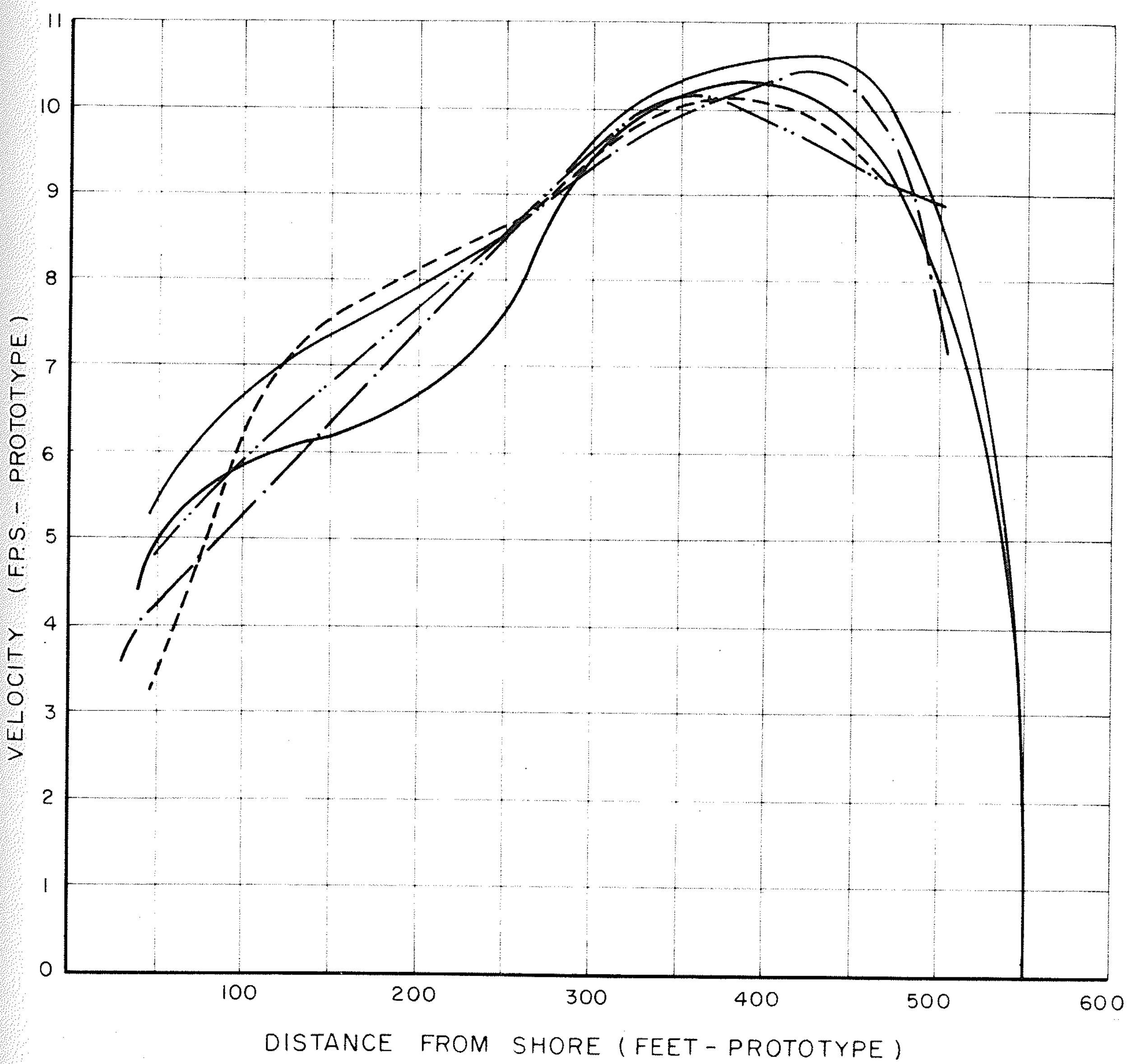


Figure 27

VELOCITY PROFILES AT CROSS - SECTION V-1

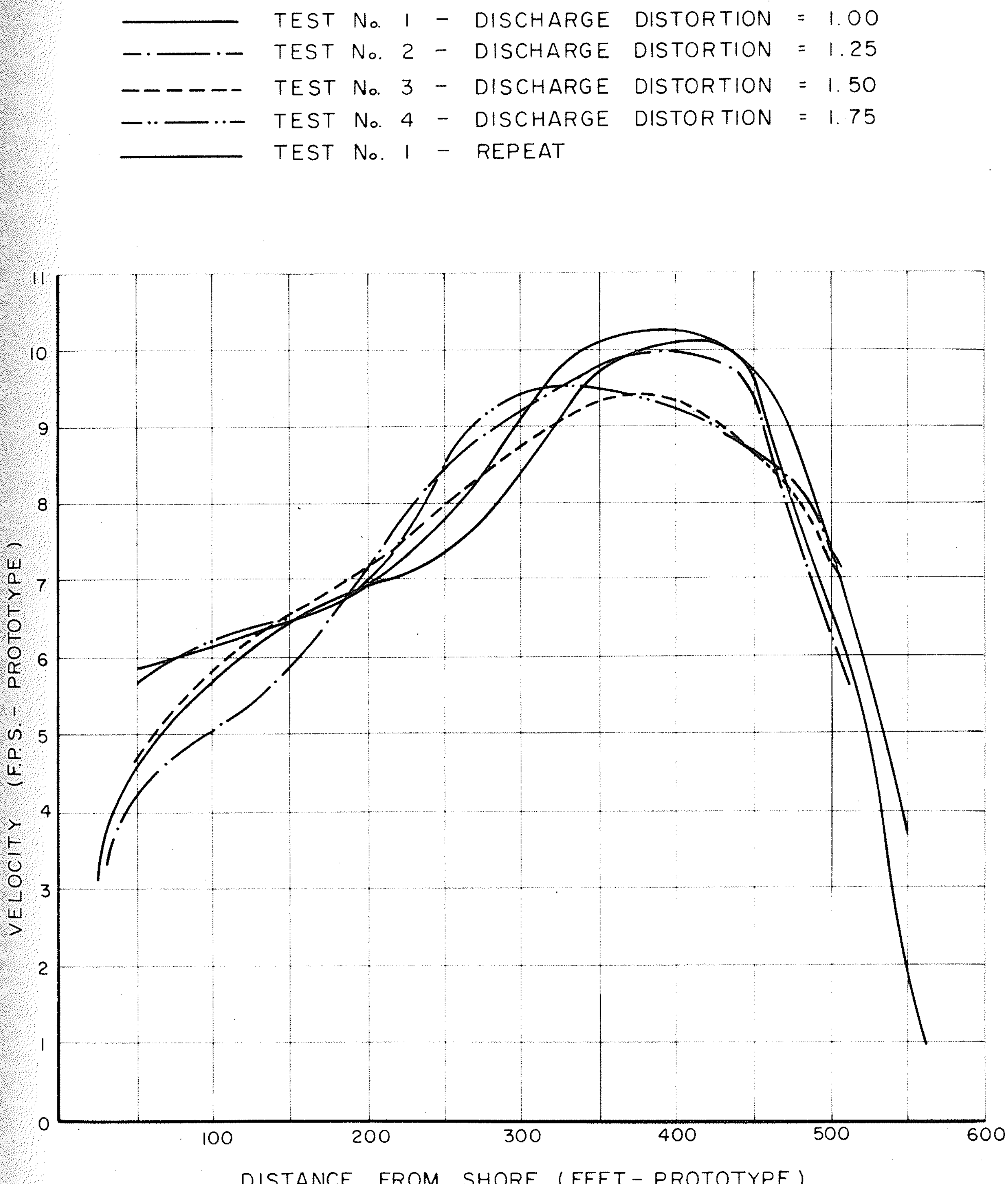
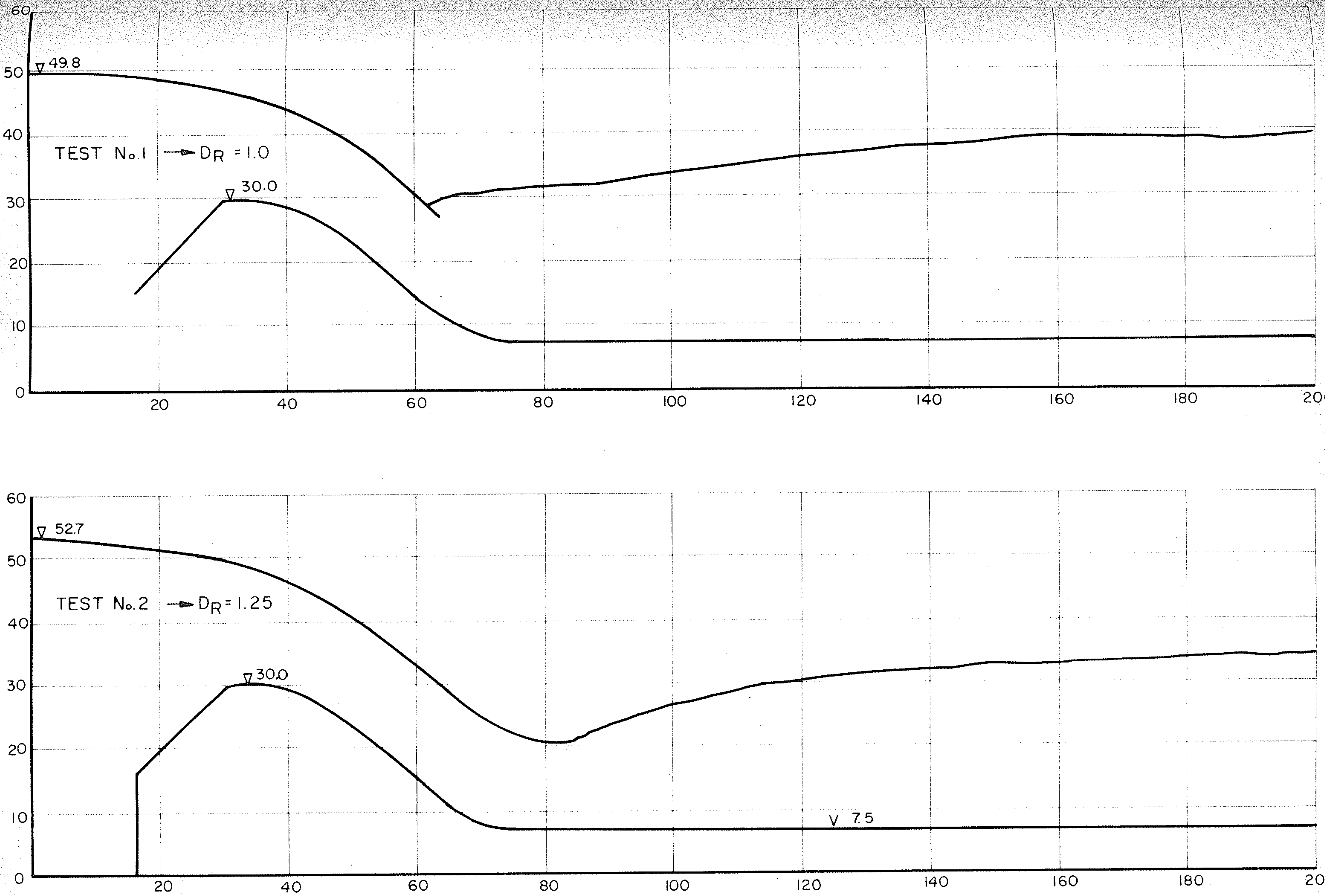
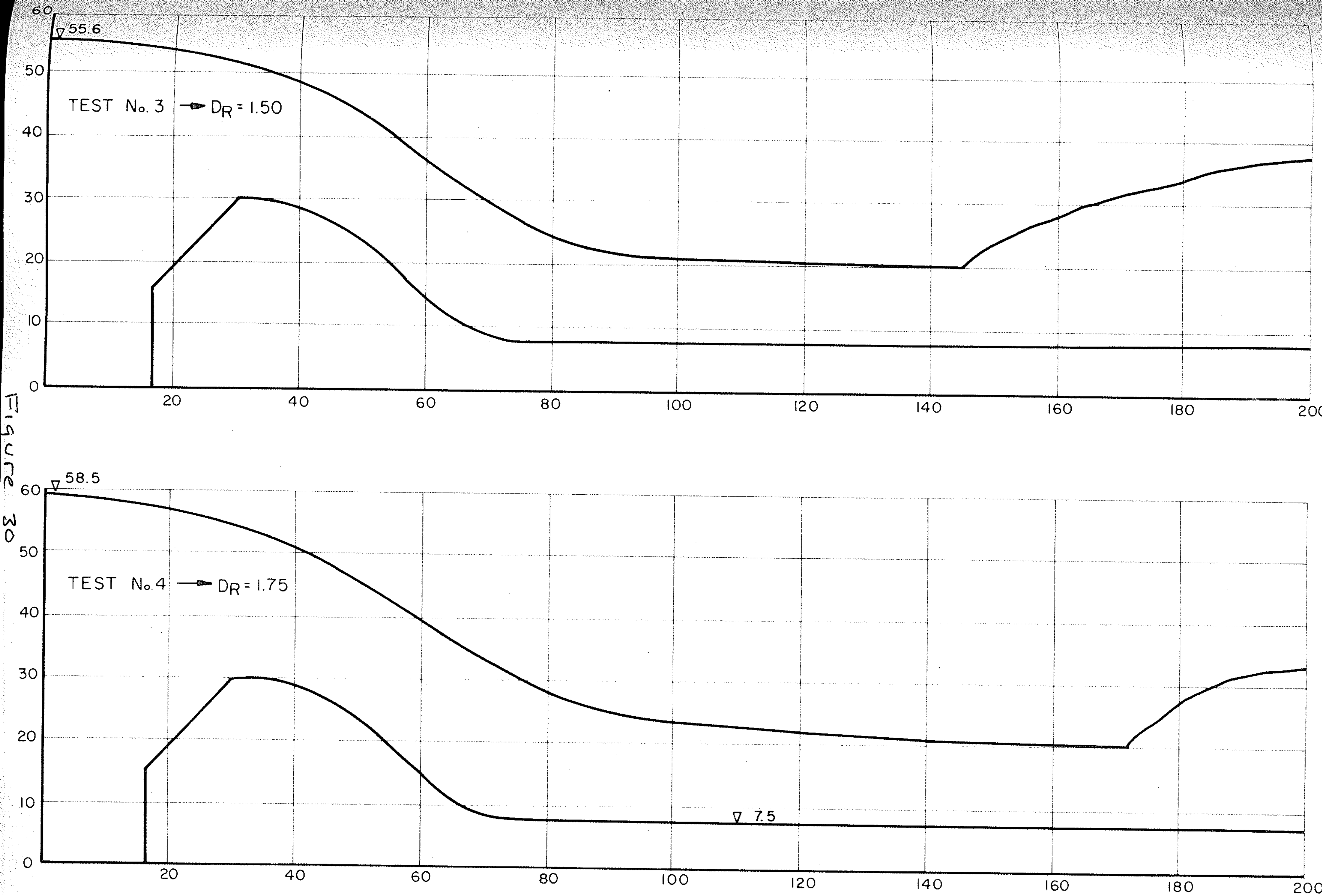


Figure 28



WATER SURFACE PROFILES Q = 60,000 T.W. = 38.0

Figure 29



WATER SURFACE PROFILES Q = 60,000 T.W. = 38.0

Figure 30

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