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Title: DISPOSAL OF SANDY PIPELINE DREDGE SPOILS BY END DUMPING

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Channel maintenance operations in the rivers and harbors of the United States annually require the disposal of over 320 million cubic meters of dredge spoils. As the availability of suitable land sites diminishes, open water disposal presents an attractive yet controversial alternative method. For open water disposal to be acceptable, the fate of the spoils which are discharged in the water must be predictable. The study described in this thesis was an effort to examine the validity, in field conditions, of an analytical model for predicting hydraulic dredge spoil fate. The analytical model was developed as part of an earlier laboratory study of open-water dredge spoiling. The model employs the vector sum of spoil particle settling velocity and forward velocity in the water to compute particle trajectory for sand spoils. The forward velocity was determined by superimposing the ambient velocity of the receiving water upon the velocity

induced by the dredge pipeline discharge. Investigation of the model in field conditions was accomplished by sampling sediment in the spoil plume from an operating hydraulic dredge, and comparing the data gathered with model predictions. The results obtained indicate the analytical model proposed is a usable means of locating spoil areas in dredging operation planning.

Disposal of Sandy Pipeline Dredge Spoils by End Dumping

by

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This thesis is dedicated to the writer's brother, a civil engineer, who has preceded him in all but graduate studies. Without his coaching and guidance, the graduate study of which this thesis is a part would not have been possible.

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DISPOSAL OF SANDY PIPELINE DREDGE SPOILS BY END DUMPING

I. INTRODUCTION

Dredging in the United States

Hydraulic dredging is founded on the principle of the transport of solids by water. Probably the first reference to such a method is Greek mythology (8), where Hercules cleaned the Augean Stables by diverting the Alpheus and Peneus rivers through them. Modern hydraulic dredging was made possible by such accomplishments as the invention of the centrifugal pump by Papin in 1705, and the cutter-head by Atkinson around 1862 (5). Over the years, the mechanics of dredging have been progressively improved. Hydraulic dredges are now capable of moving large quantities of material ranging from light silts to rock (4) over several kilometers more economically than any other method (5).

Hydraulic dredging is usually performed either to gain bottom material for fill or commercial use, or to develop and maintain navigable waterways. The majority of hydraulic dredging falls in the category of maintenance of navigable waterways, although in some instances more than one goal can be attained. In the maintenance of waterways, the spoil material is a waste product which is of little or no use, and must be disposed of in as expedient a manner as possible. This has been accomplished in the past by building sand bars where there previously were none, enlarging existing sand bars, and discharging spoils into areas of high current which would carry the material off to be re-deposited elsewhere, hopefully where it would do no harm to the channel.

Throughout the period of development of the hydraulic dredge, little attention has been paid to the problem of disposing of the spoil material. In the past, the approach used by those involved in dredging projects has been one of immediate and apparent removal of bottom material from one area to another. Little attempt has been made to locate spoiling areas on the basis of a well-founded theory; indeed, no such theory existed. Spoil areas were chosen with intended conservatism based on intuition and a knowledge of local requirements and conditions.

Increasing environmental pressure prevalent in recent years in conjunction with the continuing need for economic operation of dredging programs has brought about the need for establishment of criteria for the selection of both a suitable method and location of spoiling operations. More than 230 million cubic meters of material are dredged annually in the United States. As much as half of this volume of material is spoiled in the water, or immediately adjacent to it. Subaqueous disposal of such a large amount of waste material presents a potentially major problem. Whether simple disposal or incorporation into engineering works is proposed, the immediate fate (trajectory from discharge to bottom deposition) of the spoils should be known in advance. The present state of knowledge concerning these matters is inadequate to deal with the problem faced. The benefits of successful planning and control of dredging programs are twofold. First, more can be done to preserve and protect the natural state of known delicate ecological areas in our rivers, harbors, and estuaries; and second, we avoid the happenstance of re-dredging bottom material unwittingly spoiled in or too near a channel.

Background

A two-year study, of which this thesis is a part, was undertaken with the intent of developing a method for predetermining the immediate disposition of sandy spoils from a hydraulic dredge discharging in water. The study was divided into two phases, each running approximately one year. The entire study was based on the hypothesis that the bottom deposition point of a particular size particle could be determined if hydraulic sorting is effective, and if the velocity profile of the water and the settling velocity of the particle were known.

Phase one could best be described as a laboratory study of hydraulic dredge spoiling, and was undertaken by Y.C. Tseng (13). Phase two of the study, reported in this thesis, was an attempt to examine the basic hypothesis upon which Tseng's study was founded in field surroundings with a functioning hydraulic dredge, and in doing so to attach credence to the conclusions arrived at following the laboratory study.

Tseng's experiments showed that the velocity pattern induced into a quiescent receiving water body by a dredge jet positioned just above the water surface agreed quite well with that determined by Albertson <u>et</u> <u>al</u>. (1) for a submerged axial jet. The equation developed by Albertson is:

$$V_{x,r} = 6.2 \frac{V_o D_o}{x} \exp(-76.21 \frac{r^2}{x^2})$$

in which:

$V_{x,r}$ = longitudinal jet velocity at any point (x, r)

V_o = initial jet velocity

D_o = jet diameter

x = longitudinal distance from the jet

r = radial distance from the jet centerline

as shown in Figure 1.

Tseng chose to use the Albertson equation as a basis for an analytical model of dredge spoiling because the water velocity profile induced by the jet can be expressed mathematically. This would permit analysis of a field operation without the need for actual velocity measurements.

The analytical model developed by Tseng determines the trajectory of a given size particle by using a vector summation of the

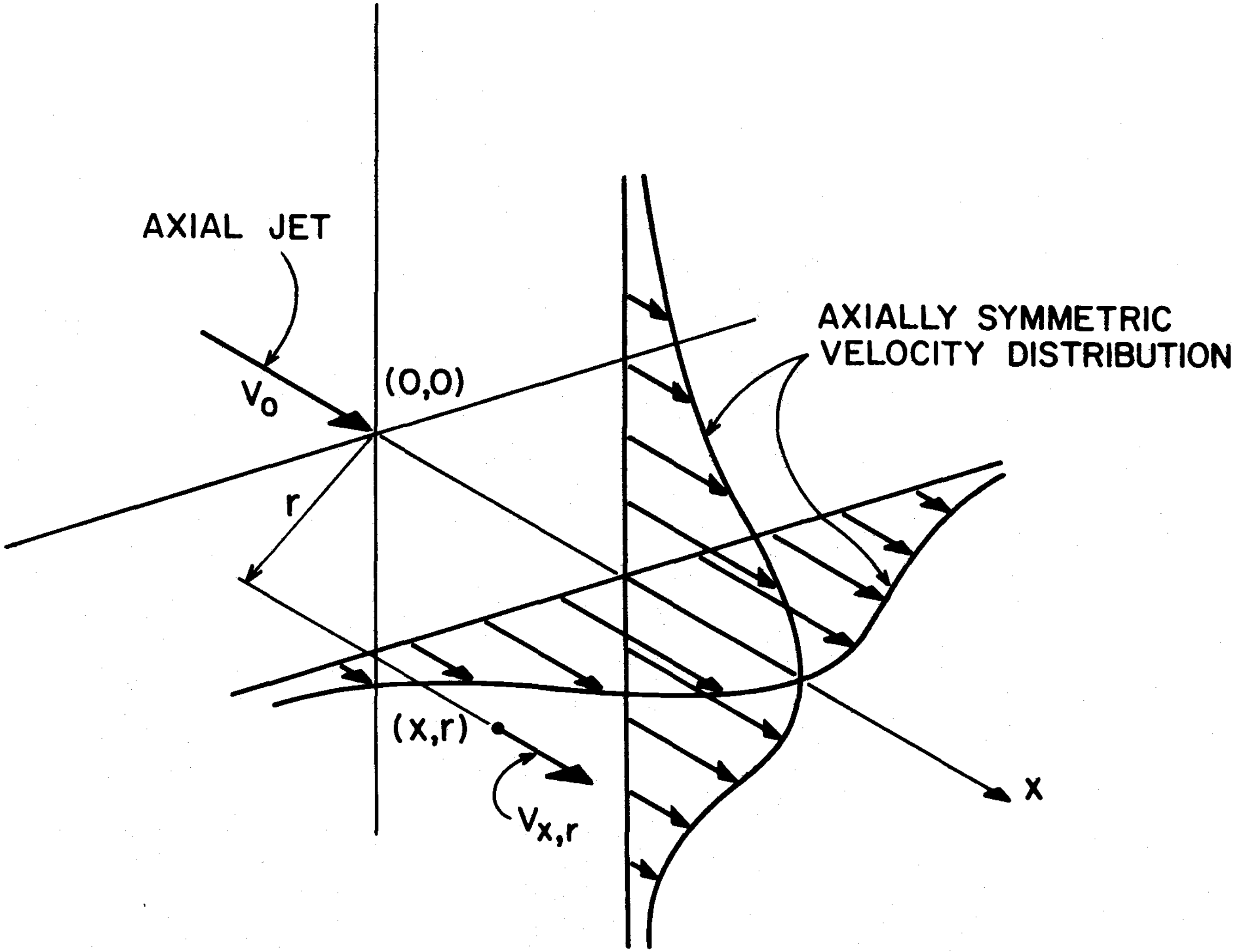

Figure 1. Velocity Profile Described by the Albertson Equation.

ambient velocity of the receiving water body, the velocity induced by the jet, and the settling velocity of the particle. Tseng attempted to confirm the model in the laboratory by collecting bottom samples from a small jet discharging sand and water in a large shallow basin. The experiments conducted were done in both quiescent water and water with a cross current flowing at 90 degrees to the jet.

A detailed presentation of the results of the laboratory study is beyond the scope of this thesis, but a list of Tseng's conclusions is a necessary groundwork for the material presented herein. Tseng (13) concluded:

Quiescent Receiving Waterbody

(1) It is an expected and observable fact that sand particles collected at a point where hydraulic sorting has acted will have uniform size, even though the sand from which they were derived may be well graded.

(2) There is poor hydraulic sorting near the jet impact point.

(3) If the velocity field in the receiving water can be determined accurately, particle trajectories can be reasonably computed.

Discharge into Cross Flow

(1) Hydraulic sorting efficiency is as effective in a cross flow as in quiescent water.

(2) Ambient cross flows with small velocities relative to the initial discharge velocity will deflect the jet centerline.

(3) A practical predictive model cannot be developed for spoil fate if the ambient velocity is complex. In only the simplest ambient flow patterns does the possibility for a workable solution become real. This solution must include the effects of deceleration of the jet by the cross flow.

Purpose and Scope

This thesis is concerned primarily with the second phase of a study intended to develop a scheme for the prediction of the immediate bottom disposition of sandy spoils discharged in water by a hydraulic dredge. This phase of the study was designed to examine in real surroundings the hypothesis that dredge spoil fate can be predicted if the velocity profile of the water and the settling velocity of the particles are known.

The approach taken was to obtain bottom samples of the spoil material being deposited from in-water discharge of a hydraulic dredge, and compare the sample locations with the locations predicted by Tseng's analytical model. In this manner, both the model and the basic hypothesis on which it is founded could be examined together.

II. FIELD STUDIES

General Procedures

The specific intent of the field studies was to examine the fate of sandy pipeline dredge spoils in two extreme receiving water conditions; first, in quiescent receiving water, and second, in receiving water with cross current flowing at 90 degrees to the dredge jet. The field studies were conducted as part of on-going dredging operations, and as such were subject to constraints that resulted in our inability to examine the exact conditions intended.

In general, the procedures used in the field were as follows. Upon arriving at the site, a number of spoil samplers were laid out in a prearranged area in an array so as to blanket the area of the spoil plume. A detailed description of the two types of samplers used appears in a later section of this thesis. On completion of the sampler array, the discharge pipe of the dredge was moved into position, and pumping begun. After a somewhat arbitrary period of time, pumping was stopped and the samplers, their positions having been noted, were retrieved.

A total of four field study sites were chosen for the project, two of these were in quiescent waters, and two of them were in water with cross current. The locations of all four sites are shown in Figure 2.

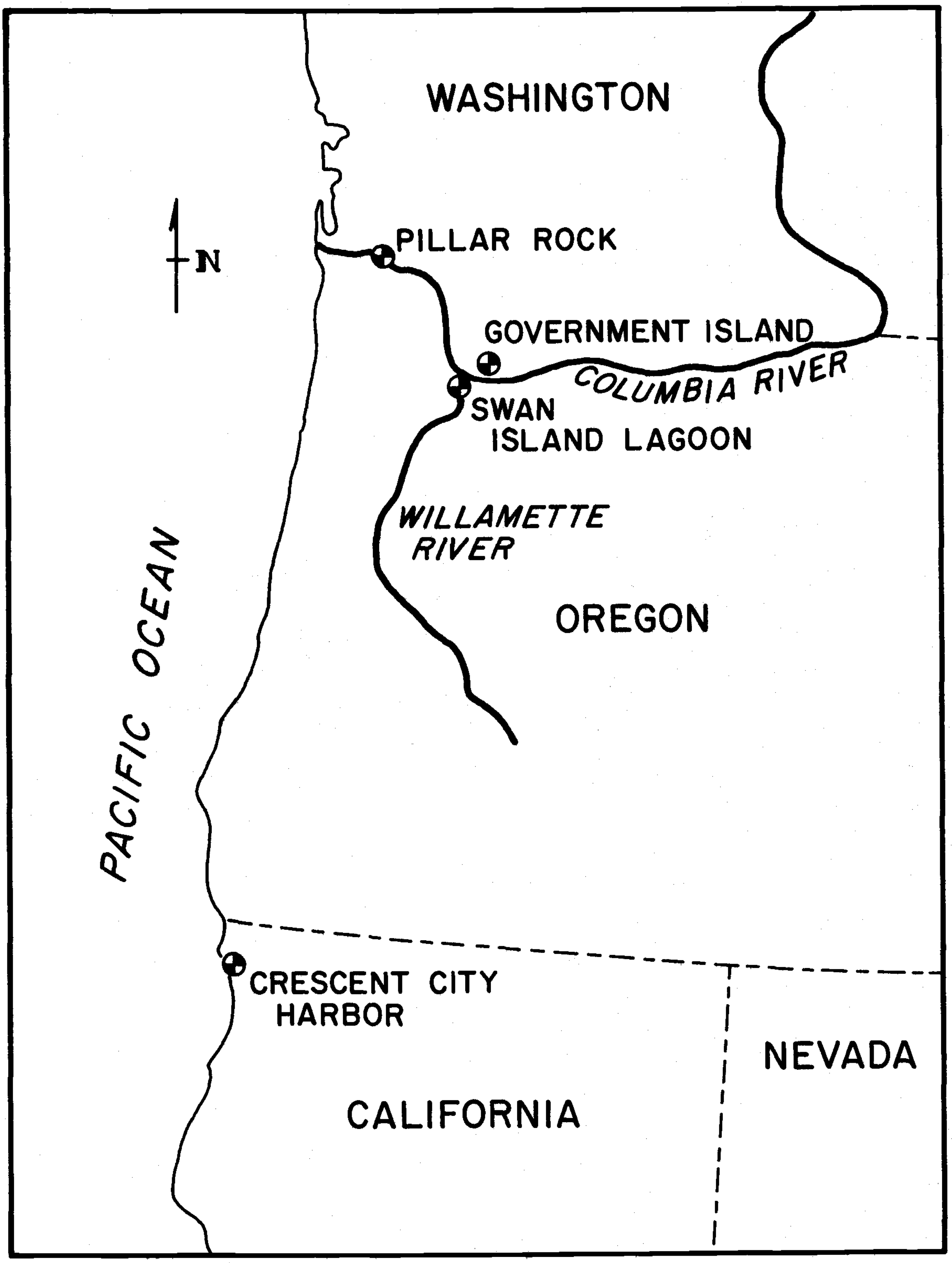

Figure 2. Field Study Location Map.

Pillar Rock, Columbia River

The sampling operations at Pillar Rock were carried out with the cooperation of the Port of Portland and the U.S. Army Corps of Engineers. The 0.76 meter (30 inch) pipeline dredge Oregon was doing channel maintenance dredging in the Pillar Rock range near River Mile 27.5, and depositing the spoil material adjacent to the water on a longitudinal sand bar opposite the channel from Pillar Rock. For the sampling operations, the pipeline discharge was located over the water, and an array of 24 samplers was laid out as shown in Figure 3. Current measurements were made during the test to determine the magnitude and direction of the ambient current, and to determine the influence of the dredge jet. The position of each sampler, each current measurement point, and the alignment and location of the discharge pipe was determined by triangulation from a baseline established on shore. The baseline was located by triangulation from known points on navigation charts.

Grain size distribution data for each of the field samples obtained are given in Appendix II, along with current meter data. A dimensionless logarithmic plot of current velocity due to the jet, versus distance along the jet centerline is given in Figure 4, and compared with the Albertson equation. An arithmetic plot of jet-induced velocity over initial jet velocity versus distance is given in Figure 5.

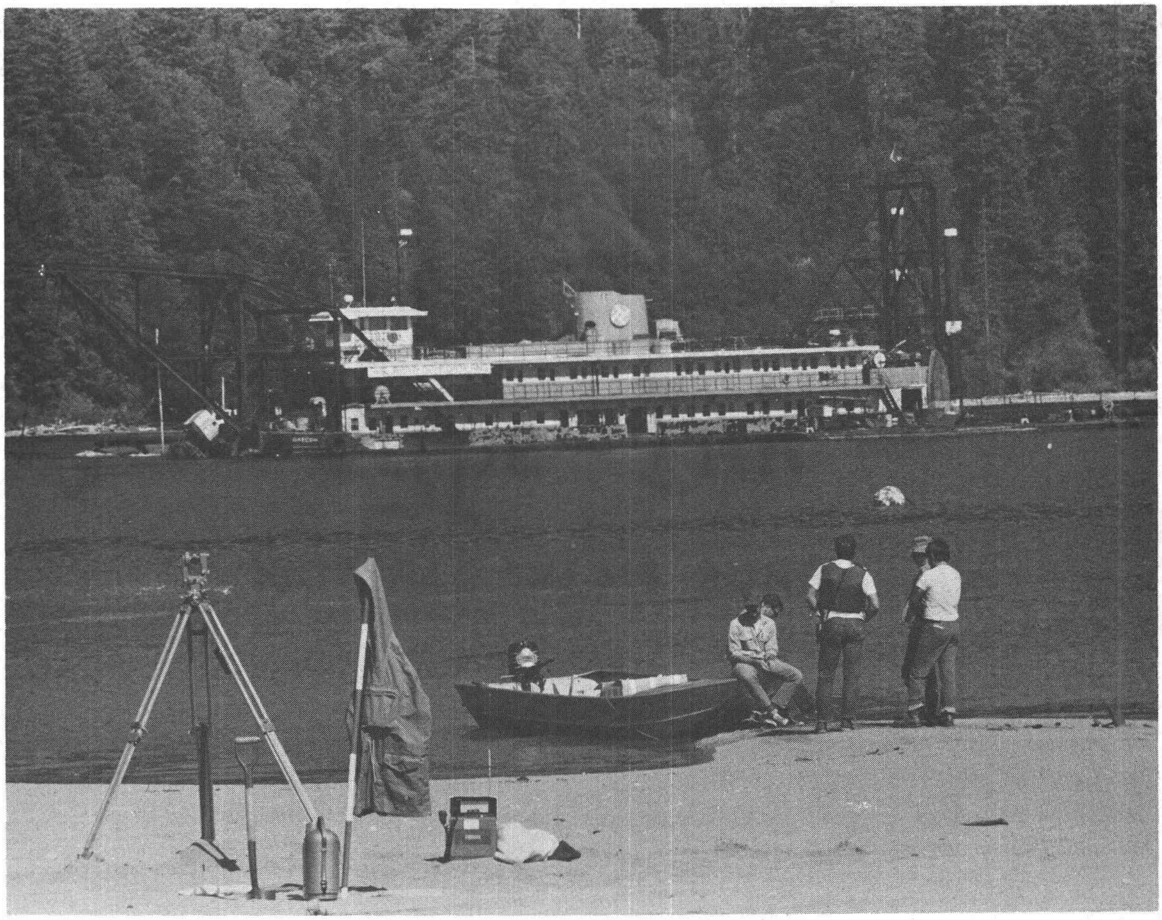

Plate 2. Pillar Rock Field Study Set-up.

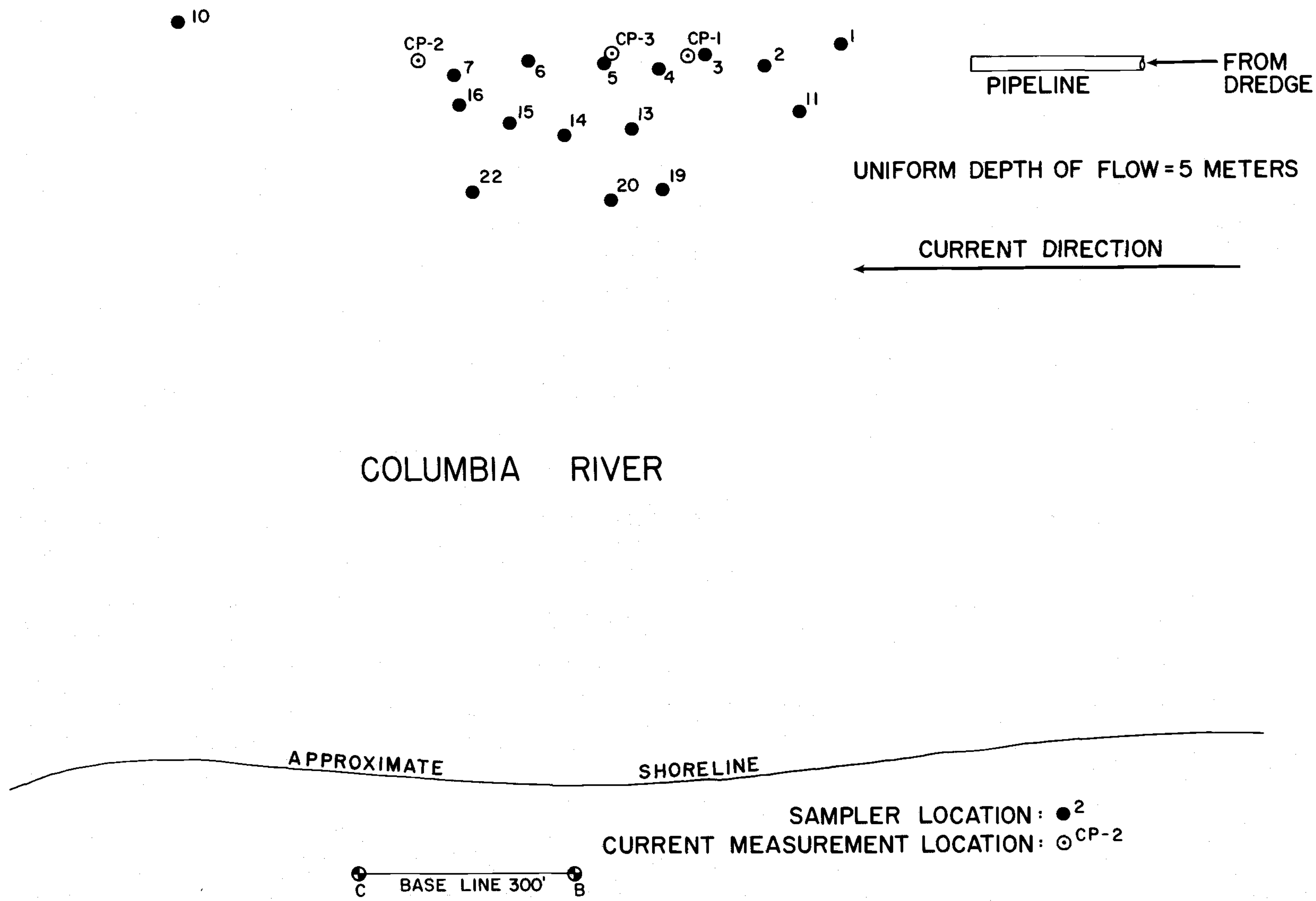

Figure 3. Field Layout -- Pillar Rock.

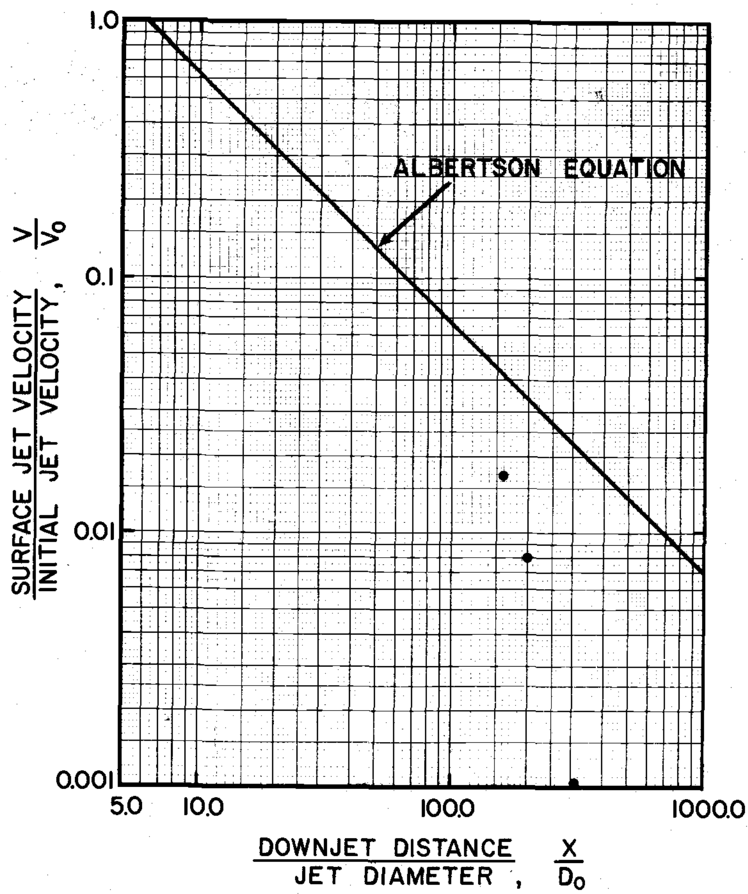

Figure 4. Surface Velocity along Jet Centerline at Pillar Rock (Logarithmic Plot).

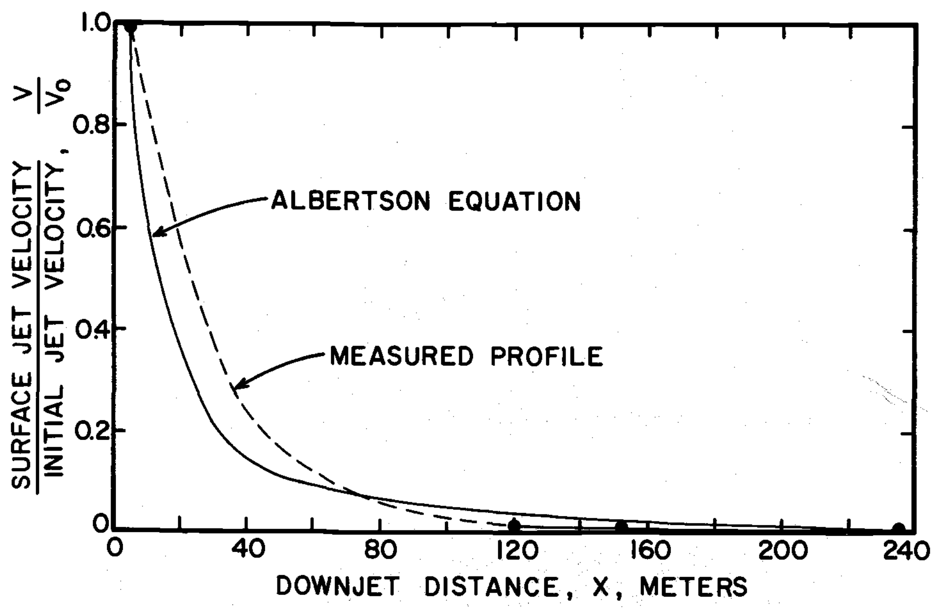

Figure 5. Surface Velocity along Jet Centerline at Pillar Rock.

The small quantity of velocity data gathered is a result of a time constraint during the in-water spoiling operation. The dredge Oregon has a capability of pumping over 40,000 cubic meters of spoil material in a 24 hour period. To avoid building a large, undesirable shoal, in-water spoiling for the purpose of our sampling lasted for only one hour. This did not give sufficient time to take more than three current measurements and accomplish the remainder of the work. Even though in-water spoiling lasted only one hour, sample No. 1, nearest the dredge jet, was entirely buried by spoil material and could not be retrieved. A tidal variation in water level greater than expected resulted in our failure to retrieve eight of the other samplers.

Government Island, Columbia River

The field operations at Government Island were carried out with the cooperation of the U.S. Army Corps of Engineers. The 0.3 meter (12 inch) pipeline dredge Luckimute was doing channel maintenance dredging on the north side of Government Island at River Mile 113.7. The spoil material was being deposited on the north shore of the island, adjacent to the water. For the sampling operations, the pipeline was disconnected, and the discharge jet was located over the water at approximately 100 degrees to the river current. An array of 23 samplers was laid out downstream from the discharge jet, and pumping was begun. Pumping continued for one hour, at which time the pipeline was re-connected, and the spoiling operations were continued on shore. During the sampling period, current measurements were made at three points downstream from the discharge jet. The positions of the current measurement points and the samplers were determined by triangulation from a baseline established on shore. The location of the baseline was determined by recording angles from the baseline to navigation markers in the area for which the positions were known. The locations of the samplers which were successfully retrieved and of the current measurement points are shown with respect to the discharge jet in Figure 6.

The grain size distribution data for each of the samples taken are given in Appendix III. Current meter data are also given in Appendix III. There was sufficient time during the pumping operation for only three current measurements.

The Luckimute is a small, shallow draft dredge designed specifically for up-river channel maintenance. As such, it is not a high capacity dredge, but nonetheless, we required the assistance of a Corps of Engineers tug to retrieve two samplers that had been partially buried by spoil material. The ambient current velocity at the site was on the order of 1 meter per second. Twelve of the samplers laid out were moved by the current during the sampling period. This movement was caused by a combination of insufficient anchor weight and inadequate length of surface line. The position of each sampler

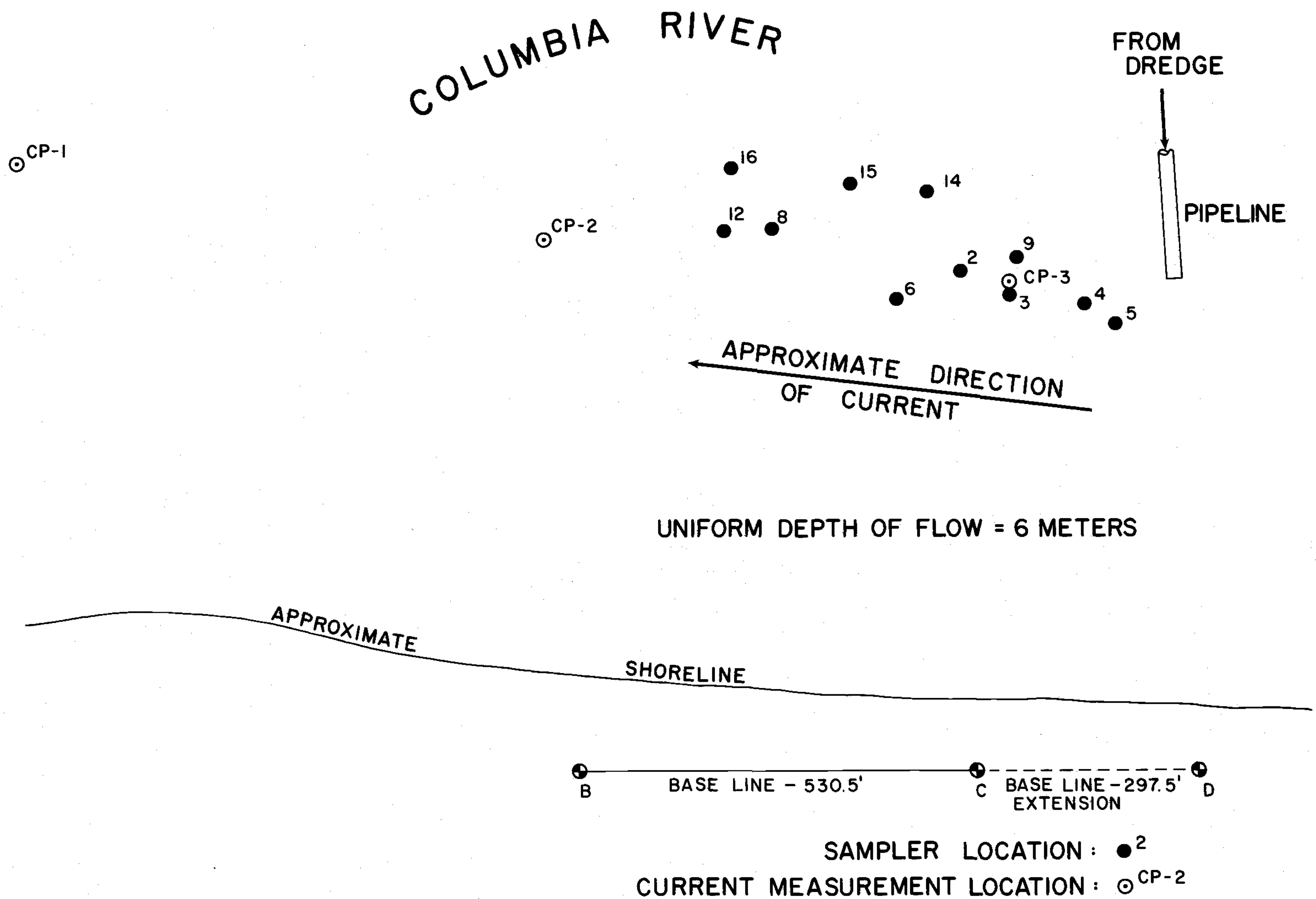

Figure 6. Field Layout -- Government Island.

was determined by triangulation, both as they were laid out and retrieved. Only the samplers which showed no movement were used for analysis.

Crescent City Harbor, California

The field sampling operations at Crescent City Harbor were done with the cooperation of the Governing Board and personnel of the Crescent City Harbor District. The dredging was done under special arrangement by the harbor dredge for the specific purpose of our field sampling operations. The dredge was located in an area believed to have a well-graded sand bottom. The samplers were laid out according to plan, but when the dredge started to pump, it was apparent that the bottom material was a marine silt or clay, and not sand.

The samples collected contained mud balls, dispersed fine sediments, and shells, and as such were of no quantitative use in the project.

Swan Island Lagoon

The field sampling operations at Swan Island Lagoon were carried out with the cooperation of the Port of Portland and the U.S. Army Corps of Engineers. The dredge Oregon, owned by the Port of Portland, was engaged in Maintenance dredging in Portland Harbor

(Willamette River) just upstream from the Port Center at Swan Island (Willamette River Mile 10). The spoil material was pumped through a buried pipe to the spoil area at the upper end of Swan Island Lagoon, and discharged into the water.

In this sampling operation the dredge was already spoiling in the water, so the sampler array was laid out while the dredge was operating. Two types of samplers were used in an effort to verify the performance of the Thackery sampler specifically designed for the project. Descriptions and specifications for the two types of samplers used are included in a later section of this thesis. A total of 23 samplers was used. The location of the samplers was determined in the same manner as on the previous tests, by triangulation from a baseline that was laid out and located for that purpose. The location and alignment of the dredge jet was determined in the same manner. The location of the samplers with respect to the dredge jet is shown in Figure 7. Of the 23 samplers laid out, only 19 were successfully retrieved. The four samplers nearest the dredge jet were buried by the spoil material and could not be retrieved. The bottom depth at the site was approximately 9.0 meters (30 feet) at the beginning of the dredging operation, but filling during the test reduced this to only 0.3 meters (1 foot) immediately in front of the dredge jet. The bottom contours as determined at the end of the test are also shown in Figure 7.

Grain size distribution data for each of the samples successfully retrieved are given in Appendix IV.

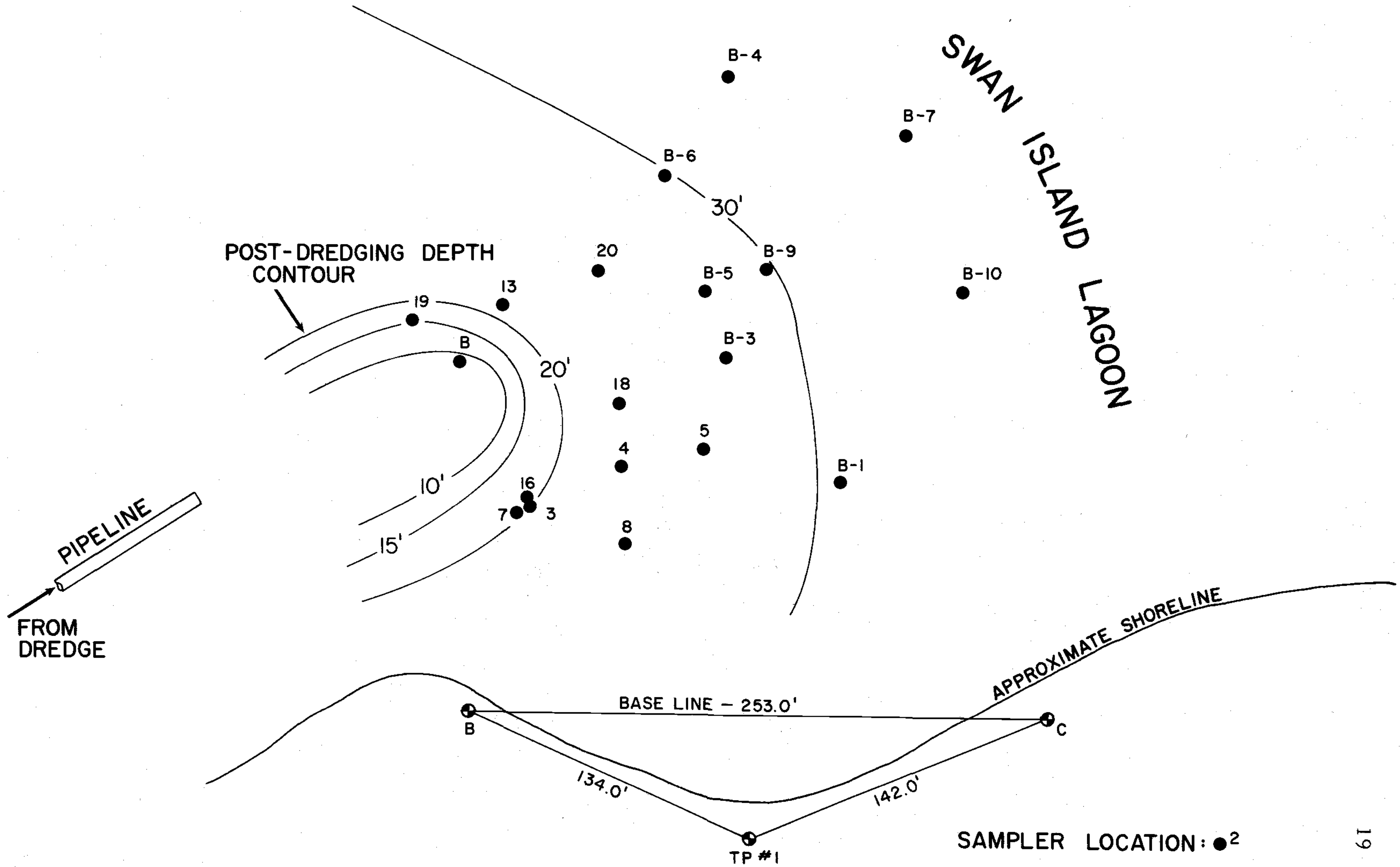

Figure 7. Field Layout -- Swan Island Lagoon.

III. SAMPLING APPARATUS

The Thackery Sampler

The first type of sampler used in the project was developed by Donald Thackery specifically for this project. The sampler was designed to float suspended just above the bottom, so that we could avoid collecting bed load sediment when sampling in rivers. The details of the sampler and its deployed configuration are shown in Figures 8 and 10. Buoyancy calculations showed that the weight required to hold the sampler and attached floats stationary was 5.7 kg (12.5 pounds). This calculation was made without consideration of ambient current patterns. The weights used on the samplers were boiler plates and lead ingots weighing from 7.25 to 10 kg (16 to 22 pounds). It was originally planned to use a cover on the samplers to prevent any of the sediment from escaping during the retrieval of the samplers. In the design of the sampler, it was found that the sediment could be prevented from escaping just as effectively by using a small entry hole in the funnel at the top of the sampler.

The samplers undoubtedly tilted downstream when located in a current, but this apparently did not seriously impair the ability of the sampler to collect sediment.

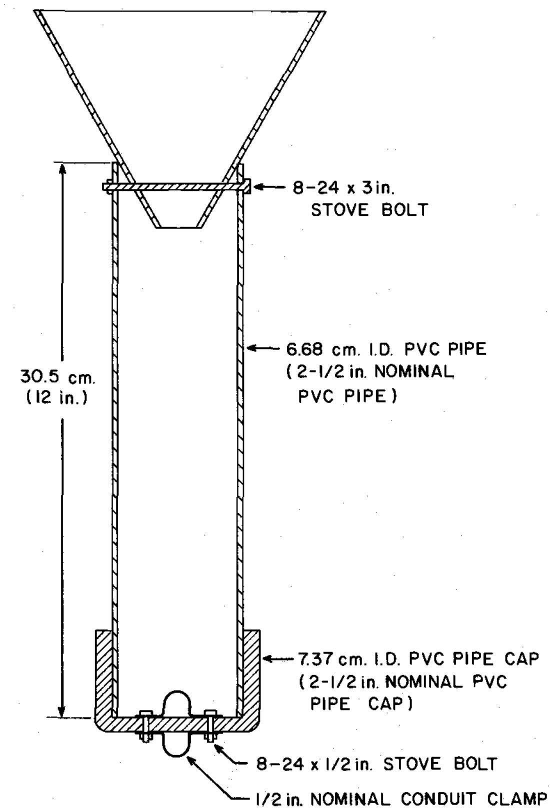

Figure 8. Thackery Sampler.

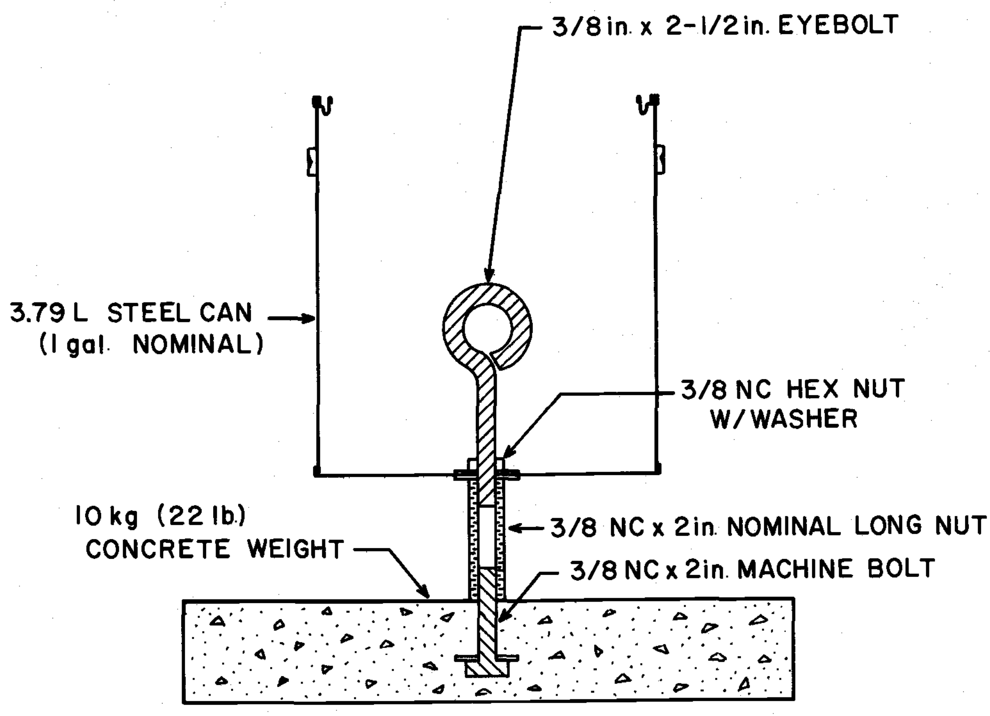

Figure 9. Bucket Sampler.

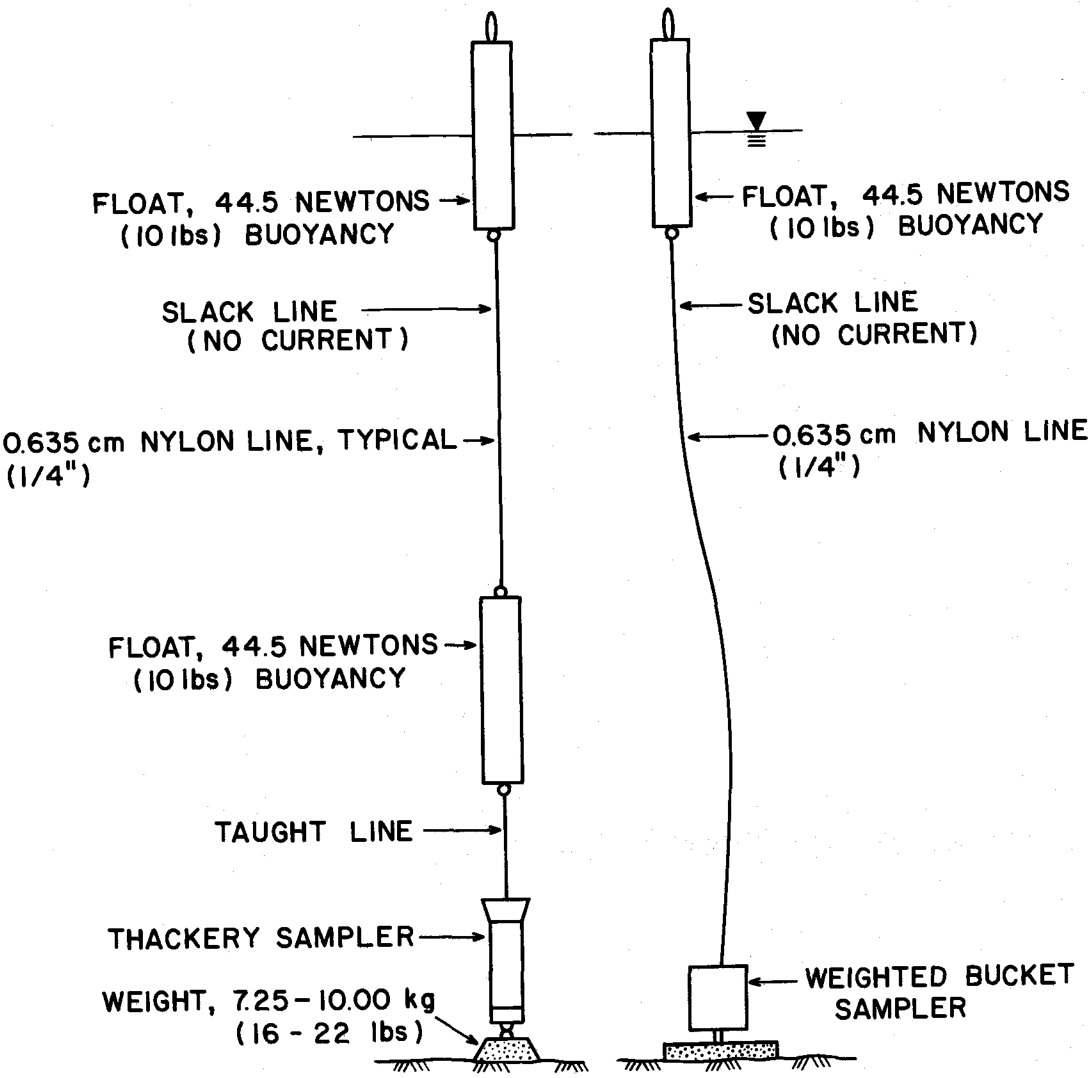

Figure 10. Spoil Samplers in Deployed Configuration.

The Bucket Sampler

For the field studies which were conducted in a quiescent receiving water body, we felt that we should augment our Thackery samplers with additional samplers to better blanket the area of the spoil plume. For this purpose, 10 bucket samplers were built. The details of the sampler and its deployed configuration are shown in Figures 9 and 10.

The sampler was intended for use only in a quiescent receiving water body because the opening was not far enough above the bottom to avoid picking up stream bed load with the sample. The sampler was originally designed with a cover which was to slide down the surface rope before pulling the sampler. The cover did not perform satisfactorily though, and was not used in the field. The anchor weight used with the bucket sampler was a 10 kg (17 lb) concrete block one foot square.

Supporting Equipment

Though not a part of the sampling apparatus, no description of sampling apparatus would be complete without at least a brief listing of supporting equipment.

Communications over the large area of each field study site were maintained using two-way radios. The location of the samplers at each site was done by triangulation from a baseline using two T1 A-E Wild Theodolites.

Current measurements were made using a standard Price current meter with a 6.8 kg (15 pound) weight.

Four different boats were used in the field operations. They were generally of the open, outboard type from 4.3 to 4.9 meters (14 to 16 feet) long.

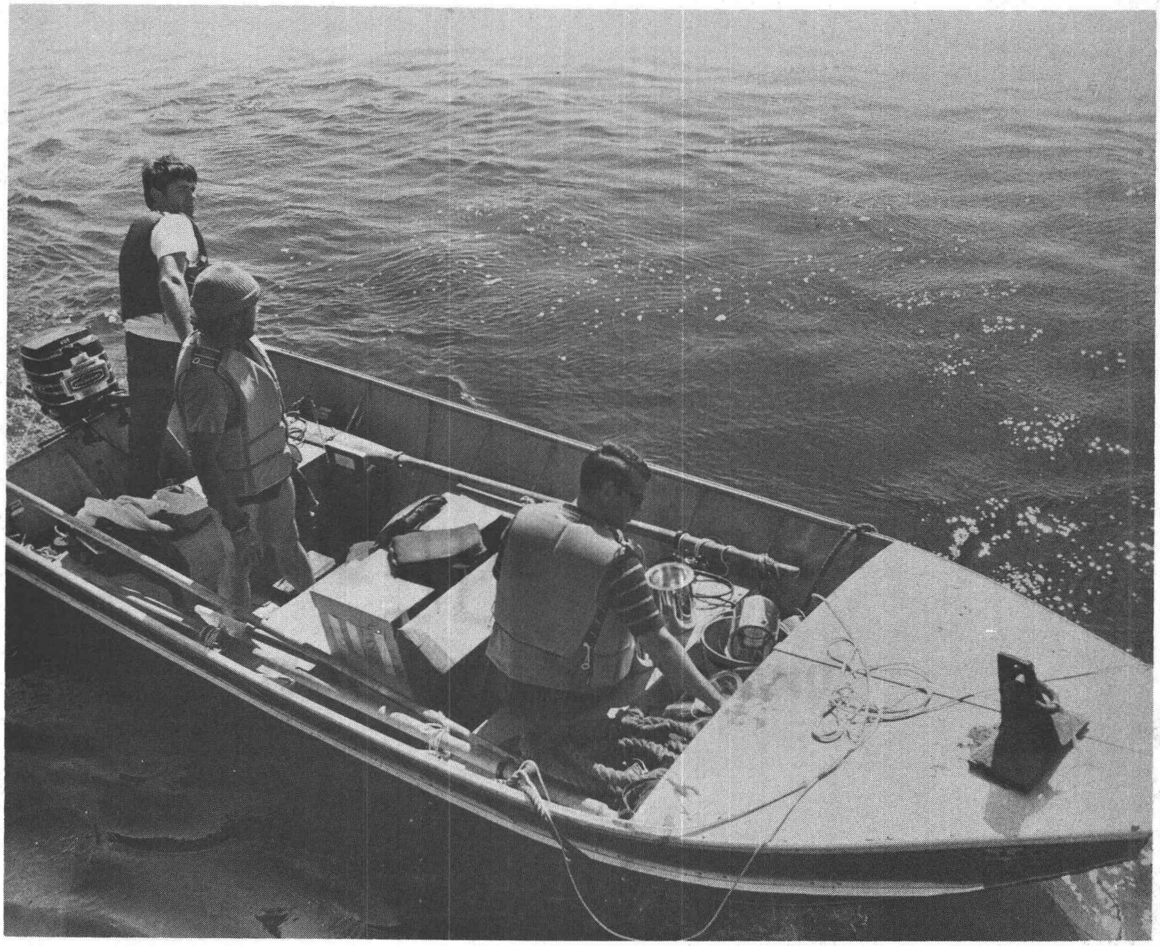

Plate 3. Open Boat Used in the Pillar Rock Field Study.

IV. DATA INTERPRETATION

Method of Data Reduction

Mechanical grain size analysis was performed on all of the sediment samples. Some means of evaluating the resulting grain size distribution curves had to be devised. One of the hypotheses on which the project is based is that hydraulic sorting will effectively separate the different grain sizes as bottom deposition takes place. Expanding on this hypothesis, we can arrive at two conditions to which the samples must adhere.

(1) A plot of the percent of a given size particle found in each sampler as a function of distance downjet (downstream) should be a spike, located at the point of hydraulic sorting for that size particle, as shown in Figure 11.

(2) At any given point downjet (downstream) a sample of the sediment should consist of only one size particle. In other words, the uniformity coefficient should equal one (uniformity coefficient is defined as D_{60}/D_{10}).

An examination of the sample data shows that neither of the above conditions are satisfied explicitly by the sample data. Because of the nature of sediment in general, and the mechanical analyses performed, it was not to be expected that the samples would adhere exactly to the conditions imposed by the hydraulic sorting hypothesis,

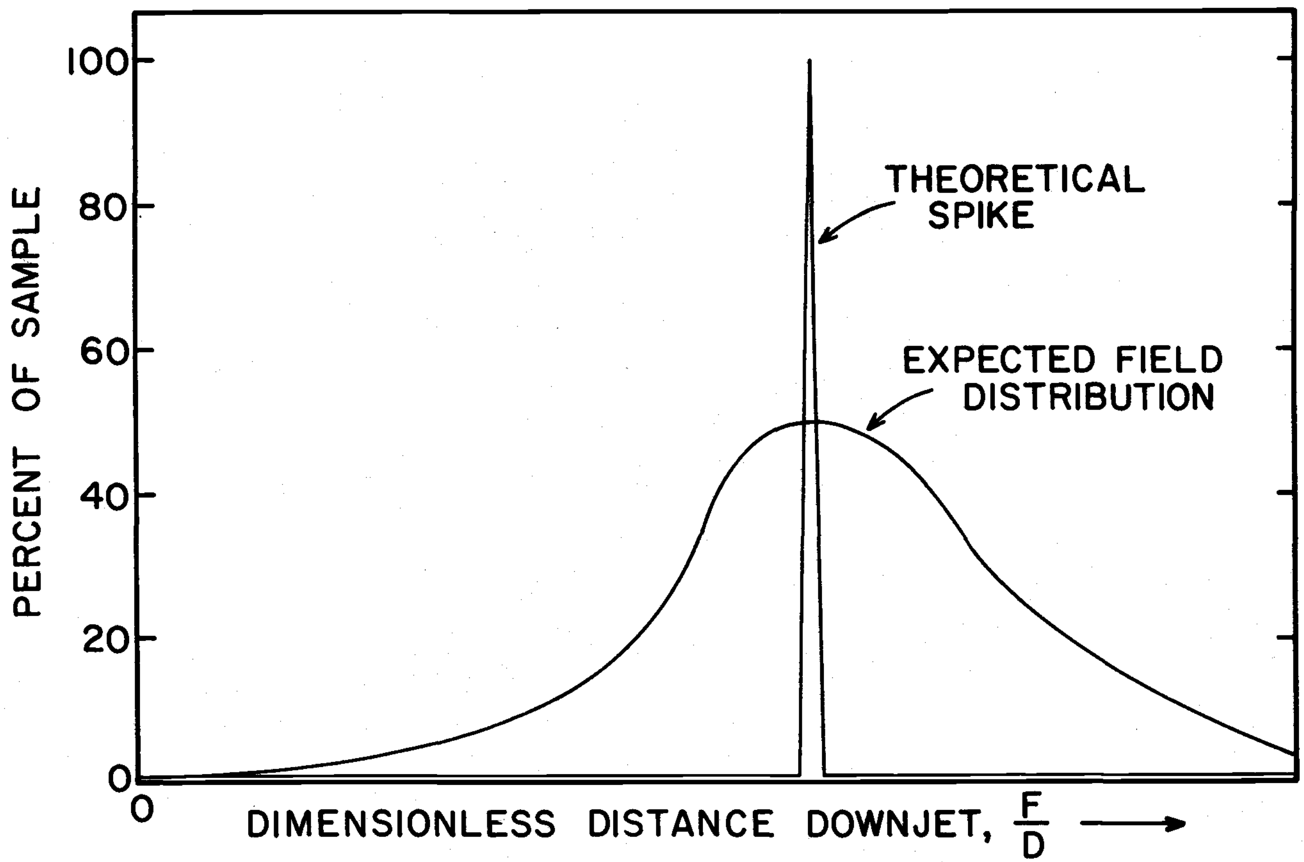

Figure 11. Conceptual Distribution of Uniform Sediment from Spoiling.

but instead depart somewhat as shown in Figure 11. Generally, the sample data do exhibit characteristic behavior of the conditions stated above.

Plots of given size particles found in each sampler as a function of distance downjet (downstream) given in Appendices II, III, and IV do show a definite maximum at some point downjet. These generally bell-shaped curves can be looked upon as "subdued" spikes similar to that shown in Figure 11. The location of the peaks in these curves can be interpreted as the location of the point of hydraulic sorting for that size-range particle.

Uniformity coefficients computed for each sample are not equal to one, but they do show that each sample is uniform, or consists of grains of nearly the same size. From this we can assume that the average particle size (D_{50}) found in any one sample represents the particle size that was hydraulically sorted and deposited at the point where the sample was taken.

We now have two methods for reducing the sample data to some form which can be compared to Tseng's mathematical model: (1) a set of locations or downjet distances corresponding to certain grain size ranges that were established from the percentage versus downjet distance curves for each field operation; and (2) the locations of each sampler, together with the average particle size from these samplers.

Analysis of Data

The reduced data from each of the field operations were analyzed by comparison of the field particle locations as determined by the methods described previously, to the particle positions predicted using the computer program given in Appendix V. The nature of the mathematical model that the computer program uses is such that the collected field data has to be used selectively. The model does not consider the effects of dispersion, and as such, can predict particle trajectories only along the center line of the dredge jet. This means that any field data that were obtained away from the center line of the dredge jet could not be expected to be in agreement with the model predictions. Data from the Pillar Rock field operation were taken from near enough the dredge jet center line to be usable. At Swan Island Lagoon and Government Island, however, some of the data taken were far off the dredge jet center line, and were not used in the comparative analysis of the model predictions and the field observations.

To use the particle trajectories computed by the mathematical model for predicting deposition point of a given size particle, it is necessary to know the bottom depth. At Pillar Rock and Government Island, the bottom depth was determined from post-dredge bathometric surveys routinely made by the Corps of Engineers for the computation of dredge volume and channel marking. At Swan Island Lagoon, we conducted our own depth soundings as we retrieved the samplers. A significant change in bottom depth would invalidate the predicted positions of the various size particles. The bottom depths used were checked with pre-dredge bathometric surveys provided by the Corps of Engineers to insure no significant bottom depth changes had occurred during the sampling operations. Changing bottom depth proved to be no real problem in data analysis because at every point where the depth was reduced significantly by spoil deposition we could not retrieve the samplers due to their burial.

V. RESULTS AND DISCUSSION

Analysis of the data for each of the field sites yielded a set of locations, or downjet travel distances observed in the field, and corresponding mathematical model distances from the computed trajectories.

The travel distances were made dimensionless by dividing them by their respective particle sizes. The dimensionless model distance was then plotted graphically versus the dimensionless field distance to evaluate the mathematical model. Plots of dimensionless model distance versus dimensionless field distance are given for each field operation in Appendices II, III, and IV. A summary plot of all three sets of points is given in Figure 12. Also shown on Figure 12 is a straight line fit to the data by the "least squares" method.

A perfect fit of model distances to field distances would be a straight line of slope equal to one, passing through the origin. The equation of the straight line fitted to the data is:

$$F' = 0.98\ M' + 25$$

where:

F' = the dimensionless field distance downjet

M' = the dimensionless model distance downjet

0.98 = the slope of the line, $\frac{dF'}{dM'}$

25 = the field axis intercept

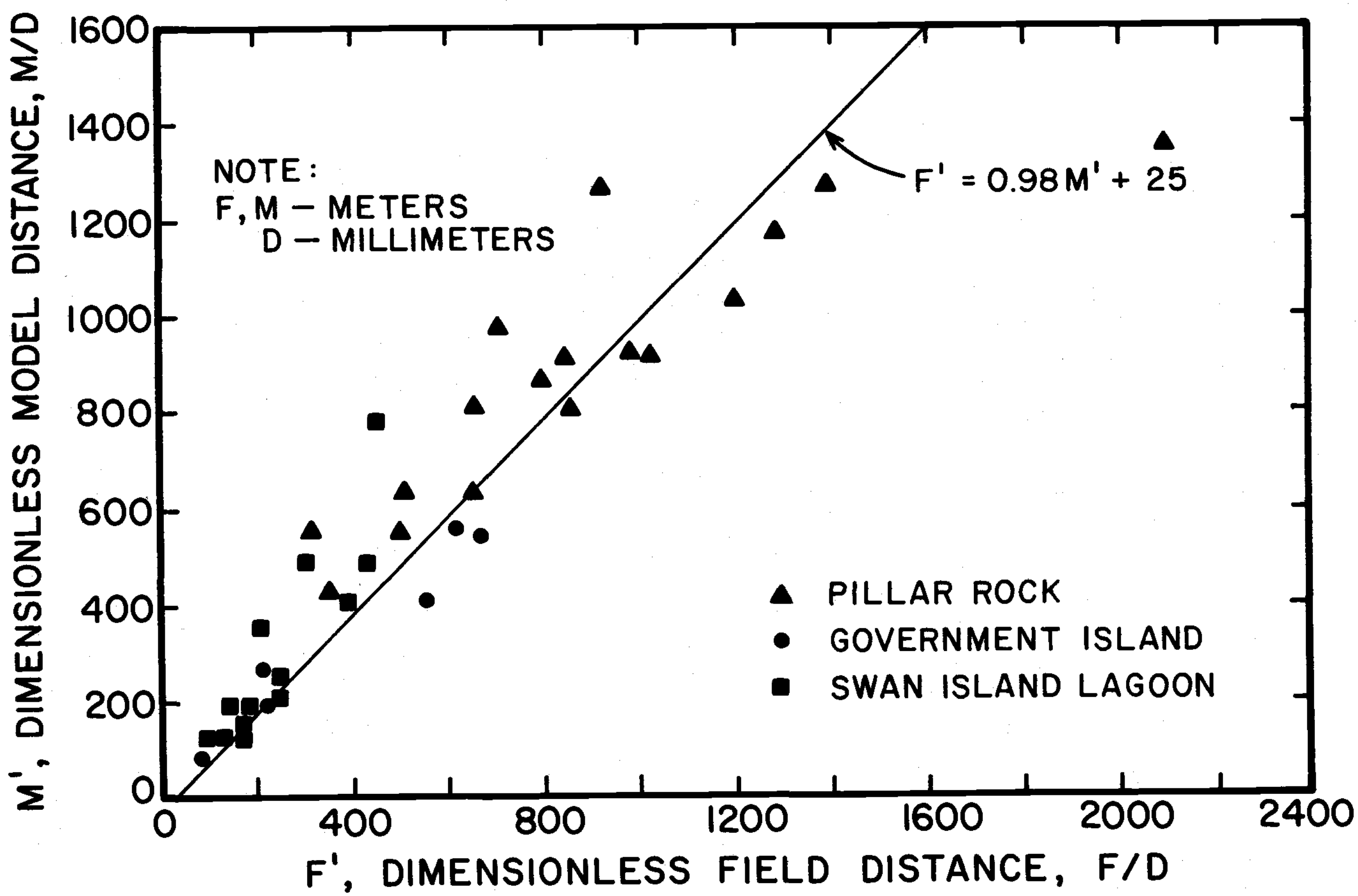

Figure 12. Summary of Predicted and Observed Spoil Locations.

The correlation coefficient computed for the data is 0.92. A correlation coefficient of 0.9 or greater indicates little scatter in the data, hence a good straight line fit.

Lack of sufficient data on velocity distributions makes it difficult to quantitatively evaluate the downjet decay of velocity observed at Pillar Rock, the only site for which velocity evaluation was planned. The data shown in Figure 4 do not fit a dimensionless logarithmic plot of the Albertson equation very well, but the arithmetic plot in Figure 5 does show a logarithmic velocity decay trend identical to that predicted by the Albertson equation.

Despite the excellent correlation of a straight line to the model versus field plot given in Figure 12, consideration of the basis for Tseng's mathematical model sheds some doubt on its validity. Albertson et al. (1) established through experimental study that the transverse distribution of velocity from a jet discharging in a quiescent reservoir is a normal distribution about the center line of the jet. Albertson also developed an empirical equation to describe the magnitude of velocity at any point in the jet as a function of position in three dimensions, with respect to the jet origin and the initial jet velocity.

Keffer and Baines (10) performed experiments on a round turbulent jet in a cross flow, and discovered that Albertson's finding of a normal distribution of jet velocity is also the case in a jet discharging normal to a cross flow. Keffer and Baines, however, did not develop a formulation for jet velocity as a function of position and initial jet velocity. Pratte and Baines (11), in studying a round turbulent jet in a cross flow, discovered that the mean jet velocity decreases much more rapidly than in a jet entering quiescent water, such as that studied by Albertson et al. The greater decrease in velocity is attributed to momentum transfer to two large counter-rotating vorticies that take up most of the jet cross section. Pratte and Baines did not develop a formulation for jet velocity as a function of position and initial velocity either.

As far as the writer has been able to discover, no researcher has successfully expressed in three dimensions the jet velocity of a jet discharging into a cross current as a function of position and initial jet velocity. Tseng's mathematical model assumes Albertson's equation describes the longitudinal jet velocity decay. If this is the case, however, there can be no turbulent vorticies in the jet because they account for some of the momentum in the jet. Since the vorticies are known to exist, Tseng's model must be invalid.

The model, even though theoretically invalid, does do a good job of predicting deposition points for sandy dredge spoils. Some explanation for this apparent contradiction is in order. Because part of the jet momentum is transferred to the vorticies, the actual longitudinal jet velocity at some distance along the jet center line must be less than that computed by the Albertson equation. The result of this would be an over-prediction by the model of travel distance for a given size particle. Pratte and Baines (11), however, observed that particles contained in the jet flow will tend to be held in the jet by the vorticies longer than if the vorticies did not exist. The result of this would be for the particles to travel further downjet than the longitudinal jet velocity alone is capable of carrying them. From these opposing arguments, we can see that the downjet travel distances predicted by Tseng's vector summation model for receiving water with cross current correspond to the observed field distances at least partially by accident.

It should be pointed out that Tseng's model is theoretically invalid only when there is some component of initial jet velocity normal to a cross current. In quiescent receiving waters, or where ambient current and jet velocity are parallel, Tseng's model is theoretically valid. In the theoretical sense, the model becomes progressively less valid as the component of initial jet velocity normal to a cross current increases to a maximum at a cross current to jet angle of 90 degrees.

Tseng's model is really a computational technique, and requires input of the various parameters describing the job. For a complete description of the input required, the reader is referred to Appendix V, which outlines the computer program used for the computation. Some discussion of two of the input parameters, ambient velocity and settling velocity, is however, necessary. In a case where the ambient current of the receiving water is not zero, some judgment of its magnitude must be made. The ambient velocities used for the field sites in this study were taken to be constants, representing the mean velocity from a velocity profile taken from the surface to the bottom of the channel. The computer program is set up to handle current velocity as a constant in both depth and distance downstream but this could be changed to handle a variation with depth without difficulty, in cases where channels are of constant depth in the downstream direction. If the channel changed depth in the downstream direction, however, a major reorganization of the computational technique used would be necessary.

The choice of settling velocity for each particular particle size can also involve some judgments. In the analysis made for this project, Stoke's Law was assumed to be valid for all the particles. For Stoke's settling to take place, the Reynolds Number for a given particle must be less than one, and preferably less than one-tenth (7). This was not true for all of the particles encountered in the field studies. In retrospect, a more judicious choice of settling velocity as given by Graf (7) might have been used.

For the largest particles sampled, the Stoke's settling velocity is greater than the actual settling velocity by a factor of at least two (7). In view of this, some explanation must be made for the apparent accuracy of Tseng's model using Stoke's settling velocities for the larger particles. The hydraulic properties of a free jet discharging into a reservoir are well documented (1, 6, 9, 12, 13), and as such are probably not the source of the incongruency. If we examine a dredge jet discharging over water, we can immediately begin to note some factors which have bearing on the computations. The dredge jet itself is above water (usually about one diameter), and in a horizontal position. The issuing stream of water and spoil material plunges downward, and depending on the discharge velocity, may enter the receiving water at an angle of from 30 degrees to 45 degrees. This in effect would impart a downward component of velocity to the spoil particles, resulting in a total downward velocity greater than the actual settling velocity and near Stoke's velocity.

VI. CONCLUSIONS

Having evaluated the results of the study in light of the characteristics of Tseng's model, some conclusions can now be drawn.

The near perfect fit of a straight line to the data plotted in Figure 12 indicates that Tseng's model can effectively predict the bottom deposition point of sandy spoils discharged from a hydraulic dredge spoiling in water. The good prediction of the model despite its theoretical shortcomings brings about some conclusions that go beyond those made by Tseng at the end of the laboratory study.

Quiescent Receiving Waterbody

(1) A vector summation model of velocity induced by a dredge jet, and the settling velocity of the particle is theoretically consistent with the hydraulics of the physical dredge spoiling operation.

(2) Hydraulic sorting of spoil material is effective in changing a well graded spoil material to a uniform deposit on the bottom, with coarse material depositing near the jet and finer material depositing progressively further away from the jet.

Receiving Water with Ambient Flow

(1) In situations where the ambient flow has a component

normal to the axis of the jet, a simple vector summation model such as Tseng's is theoretically inconsistent with the hydraulics involved.

(2) Where the ambient flow and the axis of the jet are parallel, the hydraulics involved are similar to the quiescent receiving water condition, and a vector summation model such as Tseng's is theoretically consistent.

(3) Hydraulic sorting is as effective in receiving waters with ambient flow as it is in quiescent receiving water.

The aim of this project was to develop a hydraulic dredge spoil fate model useful in the planning of economic and environmentally compatible dredging programs. The information a dredging program planner is apt to have on hand is minimal, and might include, at best, ambient current profiles, bathimetry, dredge jet velocity and diameter, and spoil grain size distribution. With this limited information, the fact that Tseng's model works overshadows the fact that it is theoretically invalid in many situations. The main aim of a dredging operation planner is to define the limits of significant quantities of spoil deposition (2). The precision involved in this is certainly on the order of tens or hundreds of meters, and additional precision is unnecessary. Additional examination of Tseng's model in a broader range of field conditions may shed further light on its applicability, but at present, the model appears to be applicable to the planning of dredging operations.

BIBLIOGRAPHY

1. Albertson, M. L., et al., "Diffusion of Submerged Jets," Transactions, American Society of Civil Engineers, Vol. 115, 1950, pp. 639-697.

2. Allen, G. W., and Conlan, D. M., "Dredge Spoil Surveillance in Shellfish Areas," Proceedings, Civil Engineering in the Oceans II, ASCE, December, 1969, pp. 823-834.

3. Boyd, M. B., et al., "Disposal of Dredge Spoil; Problem Identification and Assessment, and Research Program Development," U. S. Army Engineer Waterways Experiment Station, Technical Report H-74-8.

4. Cable, C. C., "Optimum Dredging and Disposal Practices in Estuaries," Journal of the Hydraulics Division, ASCE, Vol. 95, HY1, January, 1969, pp. 103-114.

5. Erickson, O. P., "Latest Dredging Practice," Journal of the Waterways and Harbors Division, ASCE, Vol. 87, WW1, February, 1961, pp. 15-28.

6. Fan, L. N., "Turbulent Bouyant Jets into Stratified Flowing Ambient Fields," W. M. Keck Laboratory of Hydraulics and Water Resources, California Institute of Technology, Report No. KH-R-15, June, 1967.

7. Graf, W. H., "Settling Velocity of Particles," Hydraulics of Sediment Transport, McGraw-Hill Book Company, New York, 1971, pp. 35-64.

8. Guerber, H. A. and (revised by) Stuart, M. D., The Myths of Greece and Rome, George G. Harvap and Company, Ltd., London, 1938.

9. Jen, Y., Weigel, R. L., and Mobarek, I., "Surface Discharge of Horizontal Warm Water Jet," Institute of Engineering Research, University of California, Berkeley, Technical Report HEL-3-3, 1964.

10. Keffer, J.F., and Baines, W.D., "The Round Turbulent Jet in a Cross-Wind," Journal of Fluid Mechanics, Vol. 15, 1963, pp. 481-496.

11. Pratte, B.D., and Baines, W.D., "Profiles of the Round Turbulent Jet in a Cross Flow," Journal of the Hydraulics Division, ASCE, Vol. 92, HY6, November, 1967, pp. 53-64.

12. Singamsetti, S.R., "Diffusion of Sediment in a Submerged Jet," Journal of the Hydraulics Division, ASCE, Vol. 92, HY2, March, 1966, pp. 153-168.

13. Tseng, Y.C., "Modeling Hydraulic Dredge Spoil Fate," Thesis presented to Oregon State University, Corvallis, Oregon, in 1974, in partial fulfillment of the requirements for the degree of Master of Science.

APPENDICES

APPENDIX I

NOTATION

The following symbols are used in this paper:

D = particle diameter in mm

D_o = initial dredge jet diameter in m

F = observed field distance in m

F' = dimensionless observed field distance

M = predicted model distance in m

M' = dimensionless predicted model distance

r = radial distance from the center line of the jet in m

V_o = initial jet velocity in m/sec

V_c = ambient current velocity in m/sec

$V_{x, r}$ = jet induced velocity at point (x, r) in m/sec

x, X = distance downjet in m

APPENDIX II

PILLAR ROCK DATA

Appendix Table 1. Percent Finer -- Pillar Rock.

U.S. Standard Sieve Number	Sample Number							
	2	3	4	5	6	7	10	11
20	99.9	100.0	-	99.7	100.0	-	-	100.0
40	96.7	99.2	99.4	99.2	99.2	99.6	99.2	98.5
50	80.2	88.9	93.3	95.4	96.2	98.7	97.6	86.8
60	52.3	65.2	78.4	83.2	83.2	94.7	93.7	63.3
70	27.8	40.5	52.8	58.5	63.8	82.4	82.7	38.2
80	12.0	20.7	30.1	35.0	41.6	65.4	66.9	20.4
100	3.6	8.0	11.5	16.7	22.2	42.1	46.4	8.4
200	0.5	2.0	3.8	5.6	8.7	20.2	28.3	2.4
Uniformity Coefficient	1.53	1.67	1.57	1.83	2.22	2.25	-	1.56

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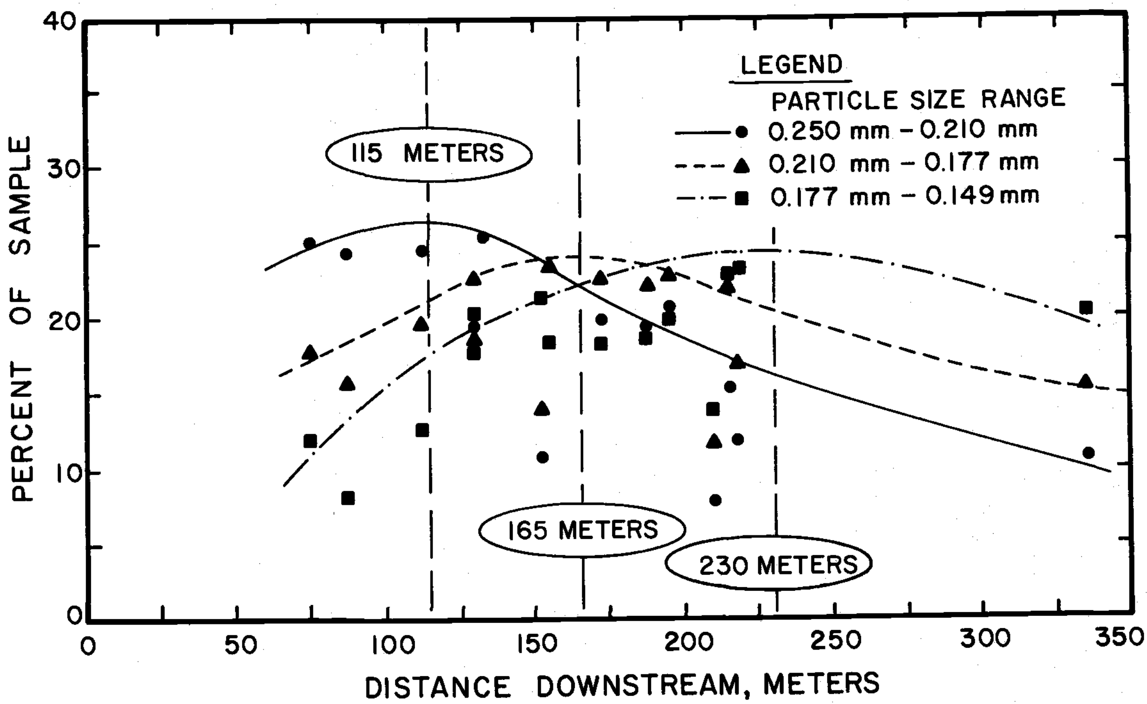
Appendix Table 1. (Continued)

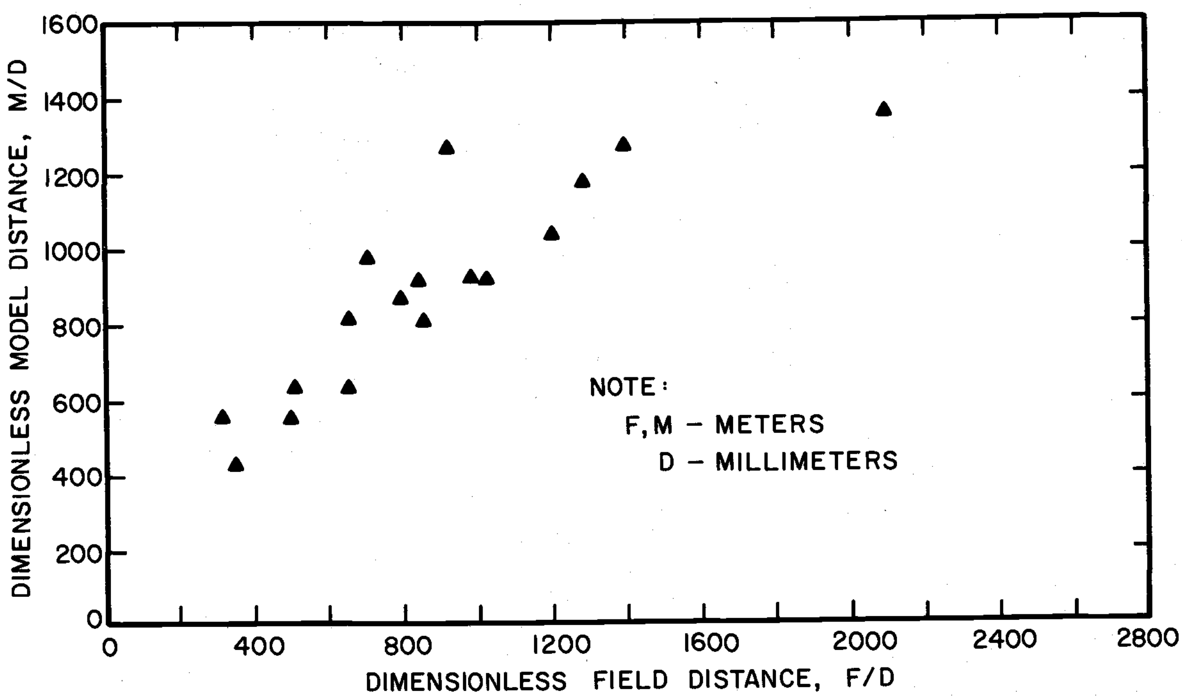
U.S. Standard Sieve Number	Sample Number						
	13	14	15	16	19	20	22
20	100.0	-	-	-	-	-	-
40	99.3	99.6	99.8	99.7	100.0	100.0	100.0
50	92.2	94.8	97.3	98.2	96.5	98.5	98.8
60	-	80.3	87.2	91.9	87.8	92.5	96.5
70	-	58.3	66.4	76.3	68.4	81.5	88.2
80	28.0	35.4	43.4	55.2	49.5	67.5	76.4
100	12.9	17.0	22.8	32.8	29.5	46.0	62.4
200	4.0	5.9	8.4	14.8	11.7	23.0	44.7
Uniformity Coefficient	1.57	1.83	2.00	-	-	-	-

Appendix Table 2. Current Measurements -- Pillar Rock.

CP-1		CP-2		CP-3	
Depth, meters	Velocity, meters/second	Depth, meters	Velocity, meters/second	Depth, meters	Velocity meters/second
0.30	0.29	0.30	0.21	0.30	0.15
1.22	0.37	1.22	0.09	1.22	0.17
2.13	0.29	2.44	0.29	2.13	0.17
3.05	0.37	3.66	0.24	3.05	0.12
4.27	0.52	4.57	0.27	3.96	0.12
5.18	0.43	5.18	0.20		
5.94	0.47	6.71	0.12		



Appendix Figure 1. Distribution of Uniform Sediment from Spoiling -- Pillar Rock.



Appendix Figure 2. Predicted and Observed Spoil Locations-- Pillar Rock.

APPENDIX III

GOVERNMENT ISLAND DATA

Appendix Table 3. Percent Finer -- Government Island.

U.S. Standard Sieve Number	Sample Number 5	4	3	9	2	14	6	15
16	98.3	98.5	99.2	-	99.7	-	-	-
20	91.9	94.0	95.6	98.4	97.4	-	99.5	-
30	74.6	76.1	83.9	89.7	86.4	98.3	96.4	95.4
40	47.9	38.0	58.9	80.9	59.6	-	79.9	81.2
50	17.3	11.2	24.4	30.5	23.1	74.4	41.3	46.6
60	9.6	7.9	15.3	20.4	14.0	51.8	26.2	27.3
80	1.9	1.3	2.7	3.7	2.4	14.2	5.2	5.5
100	0.7	-	-	0.9	-	4.8	-	2.2
200	0.2	-	-	-	-	0.5	-	0.9
Uniformity Coefficient	1.81	1.66	1.91	1.50	1.91	1.56	1.60	1.63

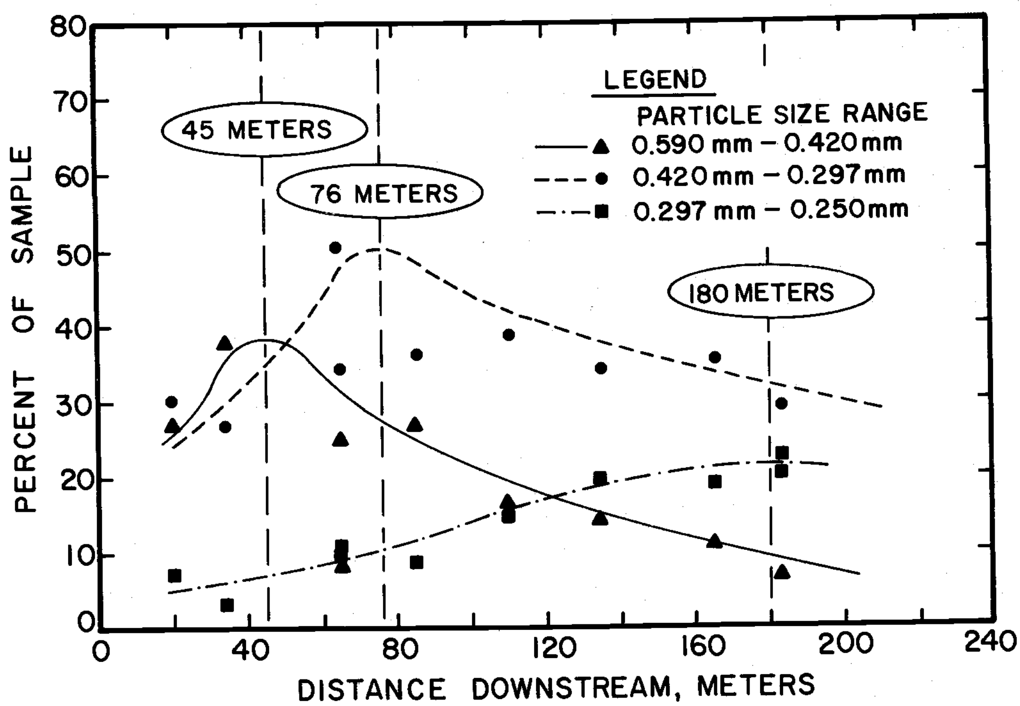
(Continued on next page)

Appendix Table 3. (Continued)

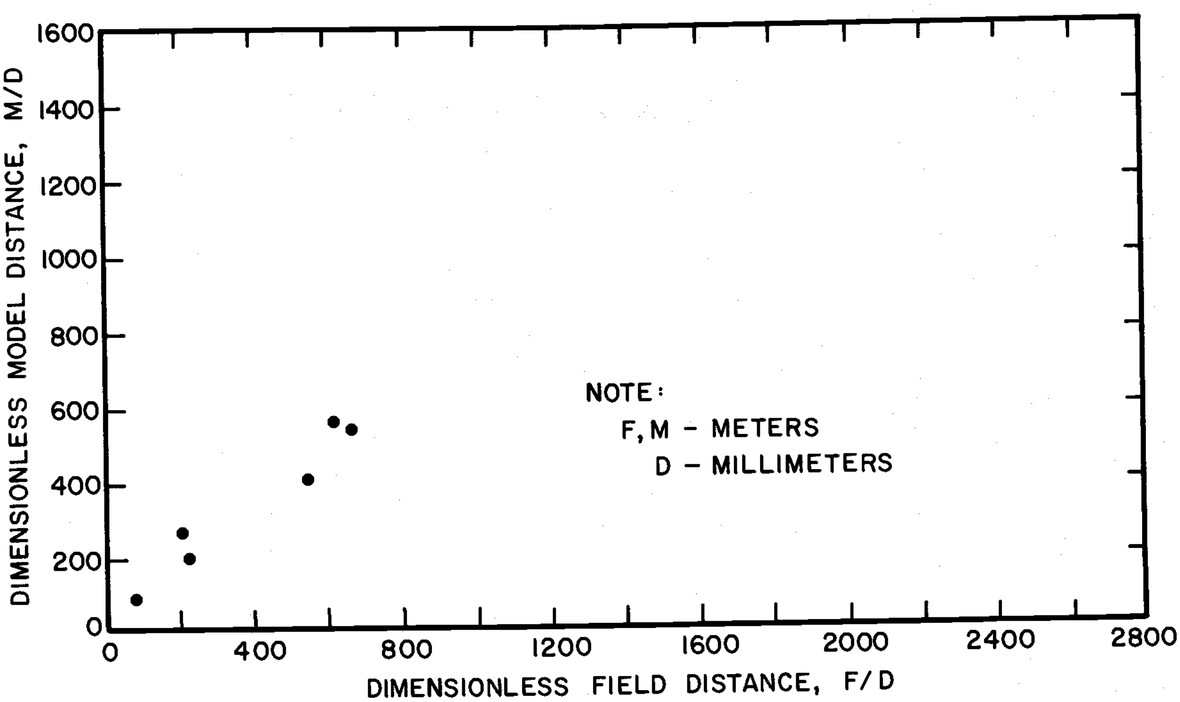
U. S. Standard Sieve Number	Sample Number 8	12	16
16	-	-	-
20	99.2	-	-
30	96.2	99.0	96.8
40	84.7	92.4	-
50	49.4	63.0	63.8
60	30.6	42.5	41.4
80	6.6	10.3	9.6
100	-	3.4	3.3
200	-	0.5	0.6
Uniformity Coefficient	1.63	1.71	1.61

Appendix Table 4. Current Measurements -- Government Island.

CP-1		CP-2		CP-3	
Depth, meters	Velocity, meters/second	Depth, meters	Velocity, meters/second	Depth, meters	Velocity, meters/second
1.52	0.96	0.91	0.99	0.61	0.84
2.74	0.84	2.44	0.87	1.52	1.02
3.66	0.81	3.66	0.79	2.44	0.96
4.57	0.81	4.88	0.88	3.66	0.91
5.49	0.67	6.10	0.70	4.57	0.96
		7.32	0.62	6.10	0.70
				7.62	0.78



Appendix Figure 3. Distribution of Uniform Sediment from spoiling -- Government Island.



Appendix Figure 4. Predicted and Observed Spoil Locations-- Government Island.

APPENDIX IV

SWAN ISLAND LAGOON DATA

Appendix Table 5. Percent Finer -- Swan Island Lagoon.

U. S. Standard Sieve Number	Sample Number							
	B-3	B-6	B	19	20	16	8	13
8	99.7	99.8	100.0	99.9	100.0	99.9	100.0	99.7
16	99.3	99.5	99.8	99.6	99.4	99.4	99.7	99.2
20	98.6	99.2	98.4	98.9	98.3	98.6	99.5	97.4
30	89.4	98.3	88.4	93.6	93.0	94.5	98.8	86.8
40	49.3	91.1	54.5	69.2	75.7	76.7	95.0	49.0
50	25.7	63.7	19.3	34.1	51.2	42.3	80.6	20.5
60	19.8	53.3	11.2	24.9	43.2	32.0	71.7	13.3
80	9.5	34.2	2.3	11.3	31.7	15.3	51.4	6.2
100	6.1	26.1	0.3	7.3	27.4	9.8	41.2	3.7
200	2.9	16.2	-	4.0	22.2	4.8	27.7	1.8
Uniformity Coefficient	2.46	-	1.91	2.20	-	2.55	-	1.91

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Appendix Table 5. (Continued)

U. S. Standard Sieve Number	Sample Number							
	18	4	5	7	3	B-4	B-1	B-10
8	99.9	99.9	99.9	99.6	99.9	100.0	100.0	100.0
16	99.5	99.6	99.7	98.9	99.5	99.8	99.9	99.9
20	97.7	99.0	99.0	98.1	98.8	99.6	99.8	99.7
30	86.7	93.7	91.6	94.9	94.5	99.3	99.2	98.8
40	44.9	60.6	55.7	80.2	70.7	95.3	94.2	89.5
50	21.4	30.7	27.5	47.9	37.2	76.2	75.4	57.9
60	15.6	29.9	20.0	36.7	27.2	66.0	66.8	46.3
80	7.8	10.9	9.5	19.2	11.3	44.7	48.6	25.7
100	5.7	7.1	6.3	13.0	5.5	34.5	40.2	17.7
200	3.8	3.9	3.4	7.0	0.0	21.6	28.3	9.6
Uniformity Coefficient	2.15	2.63	2.32	2.69	1.40	-	-	3.33

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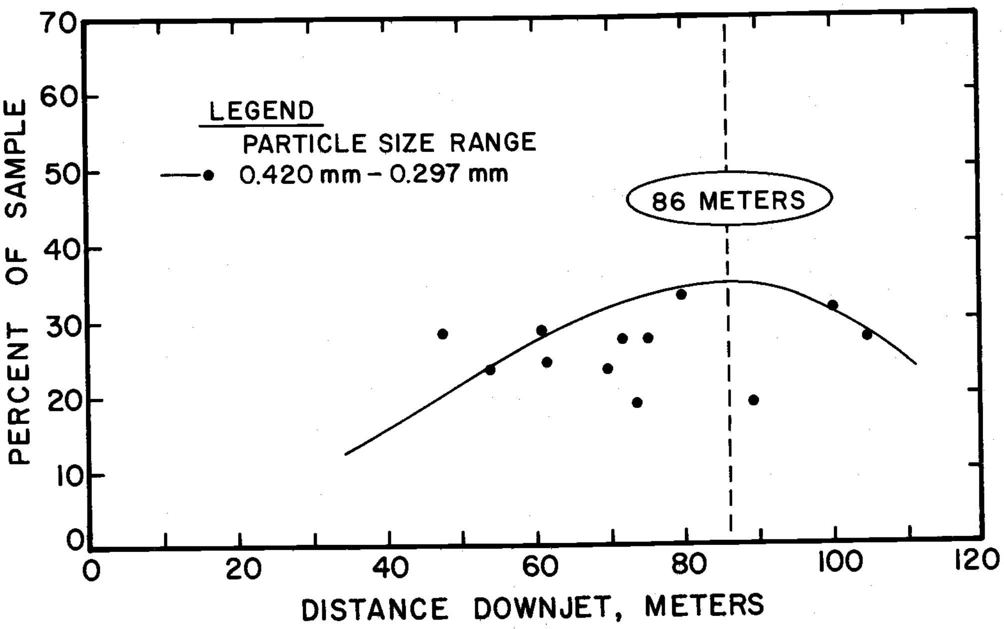
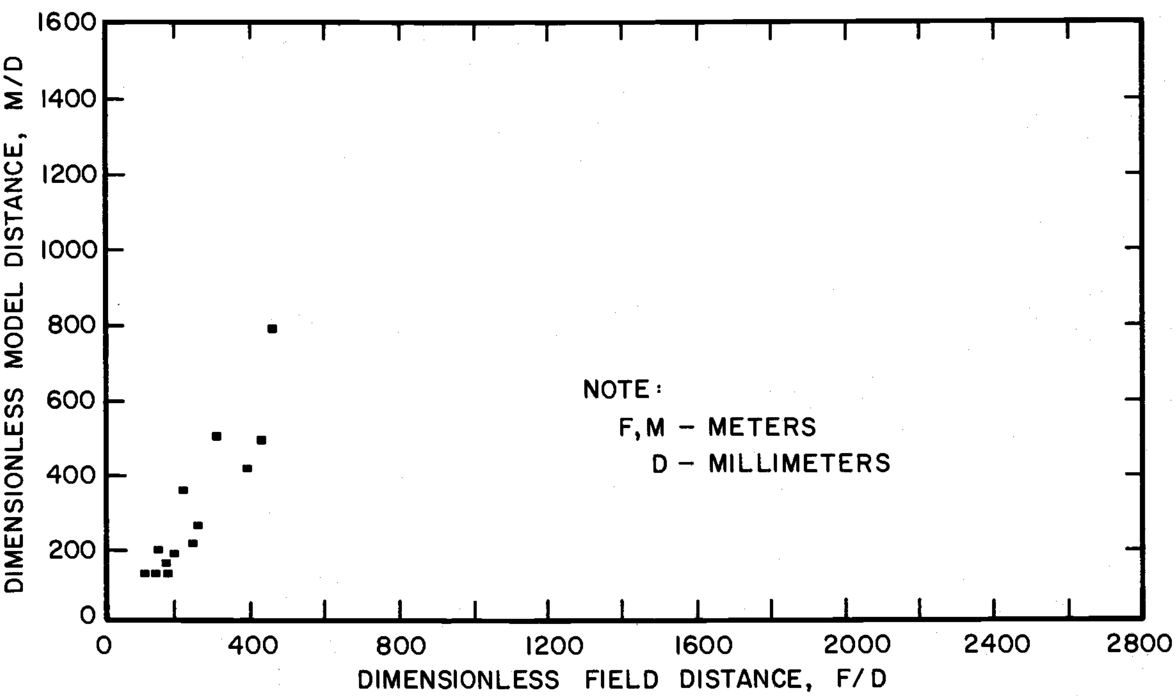
Appendix Table 5. (Continued)

U.S. Standard Sieve Number	Sample Number		
	B-7	B-9	B-5
8	99.9	99.9	99.8
16	99.7	99.5	99.2
20	99.5	99.1	98.6
30	98.7	96.3	93.4
40	90.9	75.1	59.4
50	63.2	42.3	32.2
60	53.0	32.5	25.0
80	33.7	17.3	13.1
100	25.1	11.9	9.0
200	14.9	6.1	4.8
Uniformity Coefficient	-	2.48	2.80



Appendix Figure 5. Distribution of Uniform Sediment from Spoiling -- Swan Island Lagoon.



Appendix Figure 6. Predicted and Observed Spoil Locations -- Swan Island Lagoon.

APPENDIX V

COMPUTER PROGRAM FOR THEORETICAL CALCULATION OF PARTICLE TRAJECTORIES

APPENDIX V

The program listing that follows is based on the hypothesis that the velocity vector describing the motion of a sediment particle discharged from a hydraulic dredge is equal to the summation of the ambient current velocity vector, the dredge jet included velocity vector, and the settlement velocity vector of the particle. The dredge jet induced velocity vector is determined by the Albertson equation. The settlement velocity vector is determined from Stoke's law. The program considers particle trajectories along the jet center line only, and does not include the effects of dispersion.

The program is written in Fortran IV language specifically for the Fortran compiler used with a CDC 3300 computer at the Oregon State University Computer Center. A flow chart follows the program listing.

The program is capable of handling the calculation of particle trajectory for either quiescent receiving water conditions, or receiving water with cross current at any angle to the dredge jet.

The program uses a fourth order Runge-Kutte method of numerical analysis to solve the Albertson equation describing the velocity field induced in a reservoir by an axial jet. The Albertson equation is:

$$V_{x, r} = 6.2 \frac{V_o D_o}{x} \exp(-76.21 \frac{r^2}{x^2})$$

in which:

$V_{x, r}$ = longitudinal jet velocity at any point (x, r)

V_o = initial jet velocity

D_o = jet diameter

x = longitudinal distance from the jet

r = radial distance from the jet centerline

The input variables required for the program are listed below in the order they are read by the program.

Variable	Format
BETA	F10.0
NSET	I3
VZERO, DZERO	2F10.0
VSET(K)	F10.0
DEEP	F10.0
DELTAT	F10.0
VC	F10.0

The quantities represented by the input variables are as follows:

BETA is the angle between the dredge jet and the ambient current. If no ambient current exists, BETA is equal to zero.

NSET is the number of separate settling velocities for which particle trajectories are going to be calculated.

VZERO is the initial velocity of the dredge jet.

DZERO is the diameter of the dredge jet.

VSET(K) is the subscripted variable for the different settling velocities for which particle trajectories are going to be calculated.

DEEP is the depth to which the particle trajectories are to be calculated.

DELTAT is the initial operating increment for the Fourth Order Runge-Kutte routine.

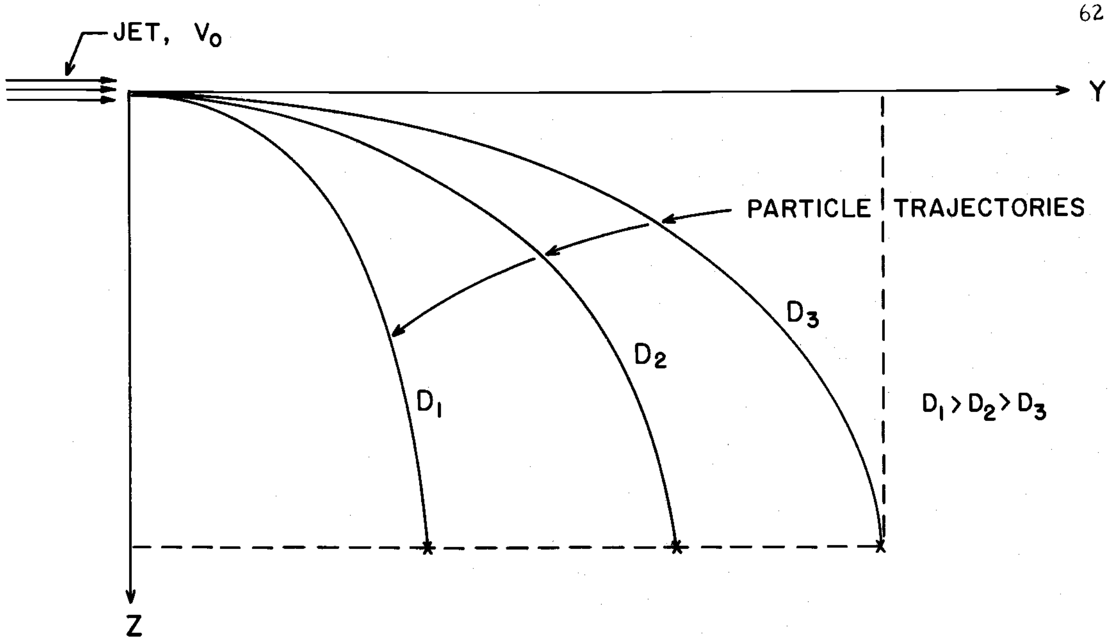
VC is the velocity of the cross current.

The program is written to operate using SI (System International) units, and the output is dimensioned in SI units.

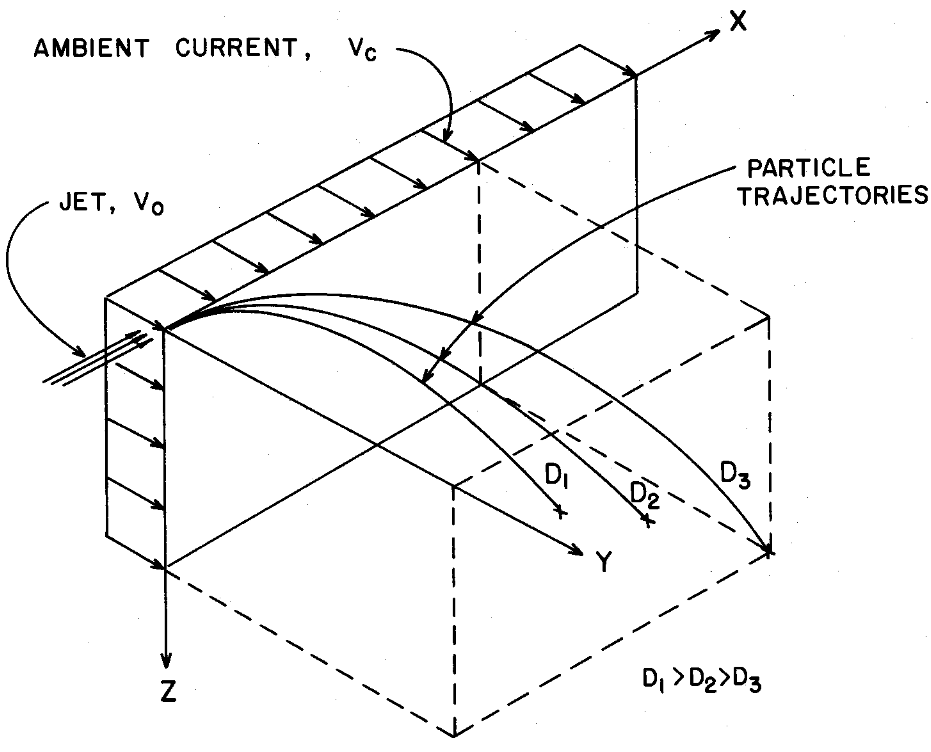
The coordinate axes are set up so that in a quiescent receiving water body, the y-axis is positive in the downjet direction, and the z-axis is positive with increasing depth. In quiescent receiving waters the x-axis has no meaning, in that the particle trajectory is two dimensional, as shown in Appendix Figure 7.

In receiving water with ambient current, the x-axis is positive in the direction of the jet, and at right angles to the ambient current. The y-axis is positive in the direction of the ambient current, and the z-axis is positive with increasing depth as shown in Appendix Figure 8.

The program is designed to minimize computer time by increasing the Runge-Kutte operating increment (DELTAT) as the Albertson equation approaches zero. The program user should make several



Appendix Figure 7. Coordinate Axes for Discharge into Quiescent Receiving Water.



Appendix Figure 8. Coordinate Axes for Discharge into Cross Current.

initial runs with different initial operating increments to determine the sensitivity of the program to changing operating increment for any one job.

Computer Program for Computation of Particle Trajectories

```
      PROGRAM DSF2
      DIMENSKON X(50, 20), Y(50, 20),Z(50, 20), S(50, 20), T(50, 20),
     CVSET(20), N(20)
      L=6
      LU=5
      READ(LU, 10)BETA
10    FORMAT(F10.0)
      READ(LU, 11)NSET
11    FORMAT(13)
      READ(LU, 12)VZERO, DZERO
12    FORMAT(2F10.0)
      READ(LU, 13)(VSET(K), K=1, NSET)
13    FORMAT(F10.0)
      READ(LU, 14)DEEP
14    FORMAT(F10.0)
      READ(LU, 15)DELTAT
15    FORMAT(F10.0)
      READ(LU, 16)VC
16    FORMAT(F10.0)
      BETA=BETA/57.3
      DO 50 K=1, NSET
      DELT1=DELTAT
```

```
      TMAX=DEEP/VSET(K)
      J=TMAX/DELT1/100.0
      C3=1.0/DELT1
      J1=5.0*C3
      IF(J-J1)30,31,31
31    J=J1
30    I=1
      JJ=1
      SCHNG=1.0
      M=1
      TT=0.0
      ZZ=0.0
      DELTAS=6.2*DZERO
      C1=DELTAS*VZERO
      S(I,K)=DELTAS
      T(I,K)=TT
      XX=DELTAS*SIN(BETA)
      X(I,K)=XX
      YY=DELTAS*COS(BETA)
      Y(I,K)=YY
      Q=YY/DELTAS
      Z(I,K)=ZZ
      SS=DELTAS
      L1=100
```

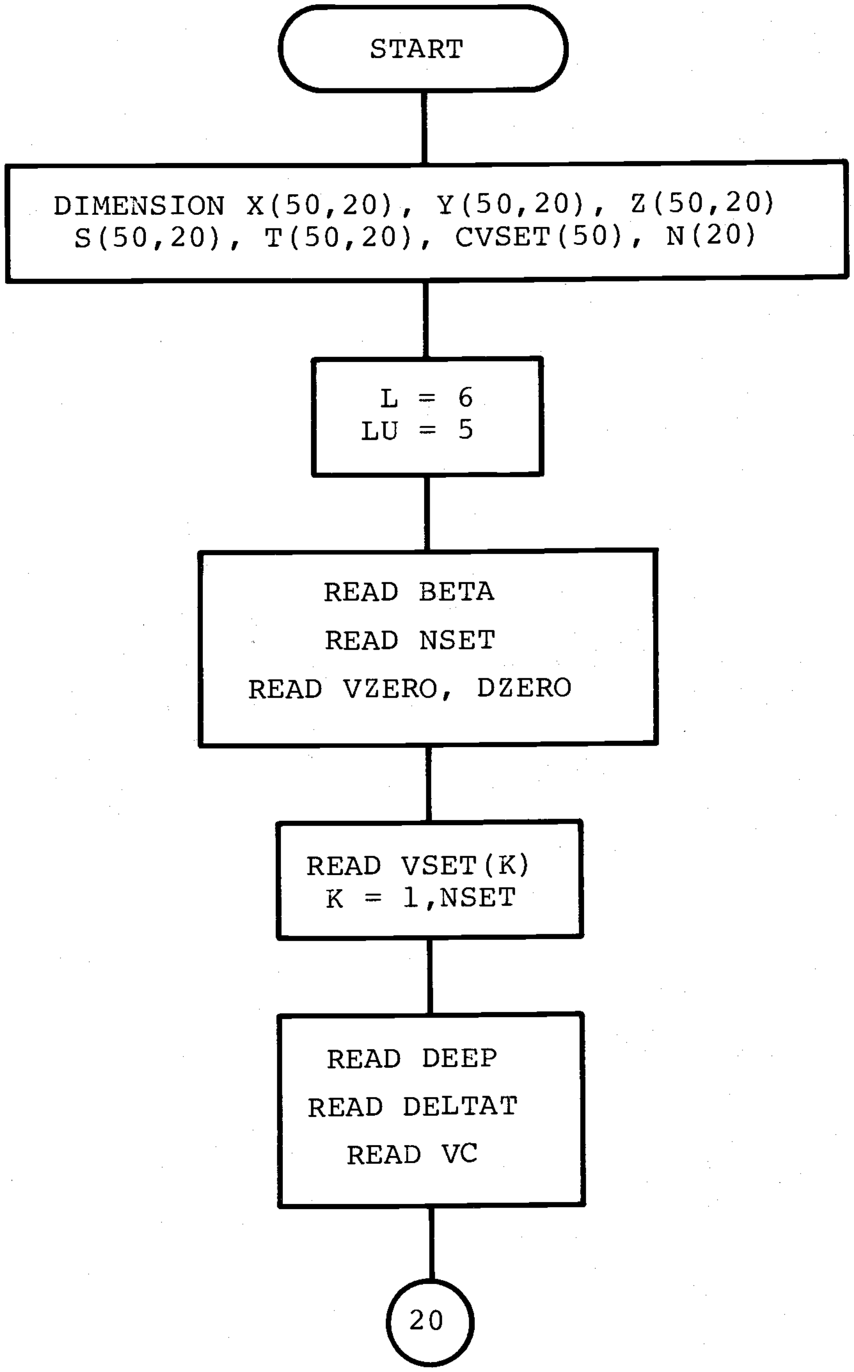
```
38      GO TO(32, 33)M
33      TLEFT=TMAX-T3
        L2=L1-I
        J=TLEFT*M/DELT1/L2
32      DELTAC=VC*DELT1
        HDELT=0.5*DELT1
        HHDELT=DELT1/6.0
        C2=-76.21*VSET(K)*VSET(K)
        XK1=C1/SS*EXP(C2*TT*TT/(SS*SS) )
        T3=TT+HDELT
        S1=SS+HDELT*XK1
        XK2=C1/S1*EXP(C2*T3*T3/(S1*S1) )
        S1=SS+HDELT*XK2
        XK3=C1/S1*EXP(C2*T3*T3/(S1*S1) )
        S1=SS+DELT1*XK3
        T3=TT+DELT1
        XK4=C1/S1*EXP(C2*T3*T3/(S1*S1) )
        TT=TT+DELT1
        DELTAS=HHDELT*(XK1+2.0*(XK2+XK3)+XK4)
        DELTAY=DELTAS*Q
        DELTX2=DELTAS*DELTAS-DELTAY*DELTAY
        IF(DELTX2)41,41,42
41      DELTAX=0.0
```

```
      GO TO 43
42    DELTAX=SQRT(DELTX2)
43    DELTAY=DELTAY+DELTAC
      DELTAS=SQRT(DELTAX*DELTAX+DELTAY*DELTAY)
      Q=DELTAY/DELTAS
      SS=SS+DELTAS
      DELTAZ=VSET(K)*DELT1
      XX=XX+DELTAX
      YY=YY+DELTAY
      ZZ=ZZ+DELTAZ
      IF(JJ-J)34, 35, 35
34    JJ=JJ+1
      GO TO 40
35    JJ=1
      I=I+1
      T(I, K)=T3
      X(I, K)=XX
      Y(I, K)=YY
      Z(I, K)=ZZ
      S(I, K)=SS
      SLOPE=DELTAX/DELTAZ
      IF(SLOPE-SCHNG)36, 37, 37
37    GO TO 40
```

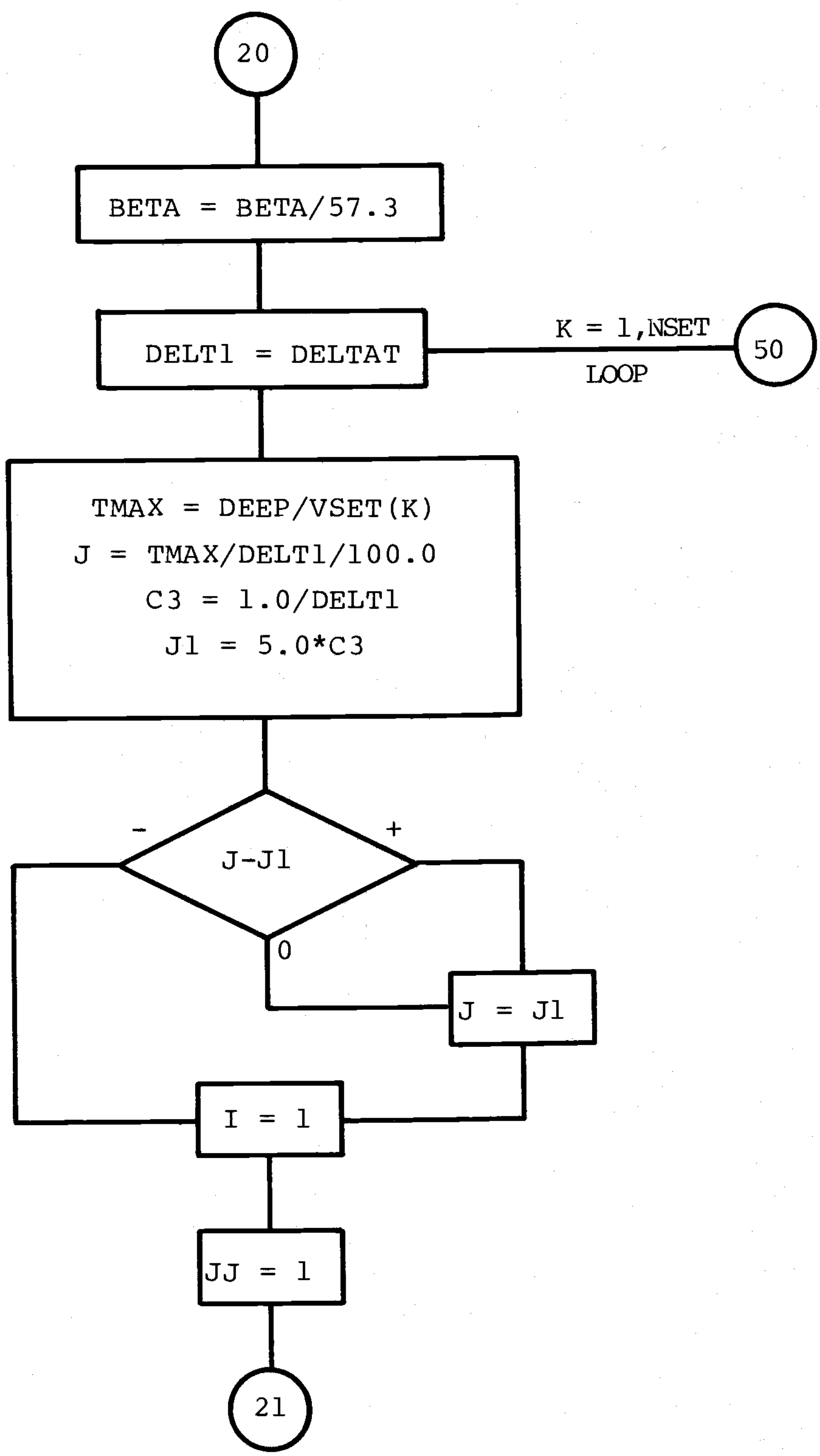
```
36      DELT1=1.25*DELT1
        SCHNG=SCHNG/1.25
        M=M+1
40      IF(T3-TMAX)38,39,39
39      N(K)=I
50      CONTINUE
        WRITE(L,57)
57      FORMAT('1','THE OUTPUT FOLLOWING IN TABULAR FORM',
       C/,'IS THE RESULT OF A COMPOSITE FOURTH ORDER',
       C/,'RUNGE-KUTTA NUMERICAL AND INCREMENTAL', .
       C/,'VECTOR SUMMATION SOLUTION OF THE ALBERTSON',
       C/,'DIFFERENTIAL EQUATION DESCRIBING A SUBMERGED',
       C/,'JET AS ADAPTED FOR THE PREDICTION OF HYDRAULIC',
       C/,'DREDGE SPOIL FATE IN A CROSS CURRENT.  FOR EACH',
       C/,'DISTINCT SETTLING VELOCITY, THE OUTPUT WILL',
       C/,'APPEAR IN FIVE COLUMNS READING ACROSS',
       C/,'1) DISTANCE ALONG THE CURVED PATH OF THE
       C/,'PARTICLE FROM THE ORIGIN, 2) THE TIME TO REACH',
       C/,'THAT DISTANCE ALONG THE CURVE, 3) DISTANCE',
       C/,'ACROSS THE CURRENT FROM THE ORIGIN AT THAT',
       C/,'TIME, 4) DISTANCE DOWNCURRENT FROM THE ORIGIN',
       C/,'AT THAT TIME, AND 5) DEPTH TO WHICH THE
       C/,'PARTICLE HAS SETTLED AT THAT TIME.',/)
```

```
      WRITE(L, 70)VZERO, DZERO,BETA, VC, DEEP
70    FORMAT(/, ' THE INPUT VALUES ARE AS FOLLOWS:', /
     C, 'INITIAL DREDGE JET VELOCITY, VZERO=', F6.3, 'M/SEC', /
     C, 'DREDGE JET DIAMETER, DZERO=', F6.4, 'M', /
     C, 'CURRENT DIRECTION/JET DIRECTION ANGLE, BETA='
     C, F6.3, 'RAD', /
     C, 'CROSS CURRENT VELOCITY, VC=', F6.3, 'M/SEC', /
     C, 'DEPTH TO TERMINATE CALCULATION, DEEP=', F6.3,
     C, 'M', /)
      WRITE(L, 51)
51    FORMAT('1')
      DO 52 K=1, NSET
      WRITE(L, 53)VSET(K)
53    FORMAT('SETTLING VELOCITY=',F10.6, 'M/SEC', //)
      WRITE(L, 54)
54    FORMAT(7X, 'S, ',9X, 'T, ',14X, 'COORDINATES, M', /
     C, 3X, 'DISTANCE, ', 4X, 'TIME,', 8X, 'X, '9X, 'Y, ', 9X, 'Z, ', /
     C, 6X, 'M', 9/, 'SEC', 8X, 'ACROSS DOWNSTREAM', 4X, 'DEPTH', //)
      NU=N(K)
      DO 55 I=1, NU
      WRITE(L, 56)S(I, K), T(I, K), X(I, K), Y(I,K), Z(I, K)
56    FORMAT(1X, F9.2, 1X, F10.2,1X, F10.2, 1X, F10.2, 1X, F10.2)
55    CONTINUE
```

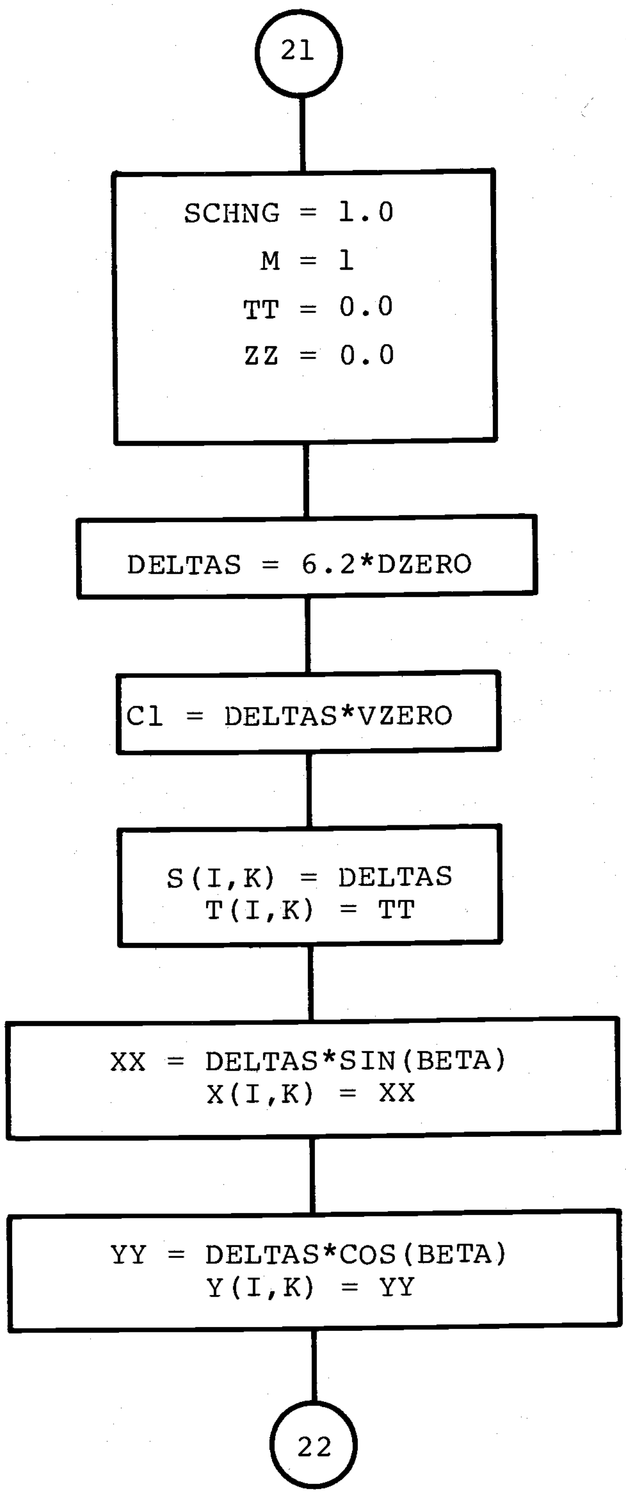
```
52      WRITE(L, 51)
        STOP
        END
```



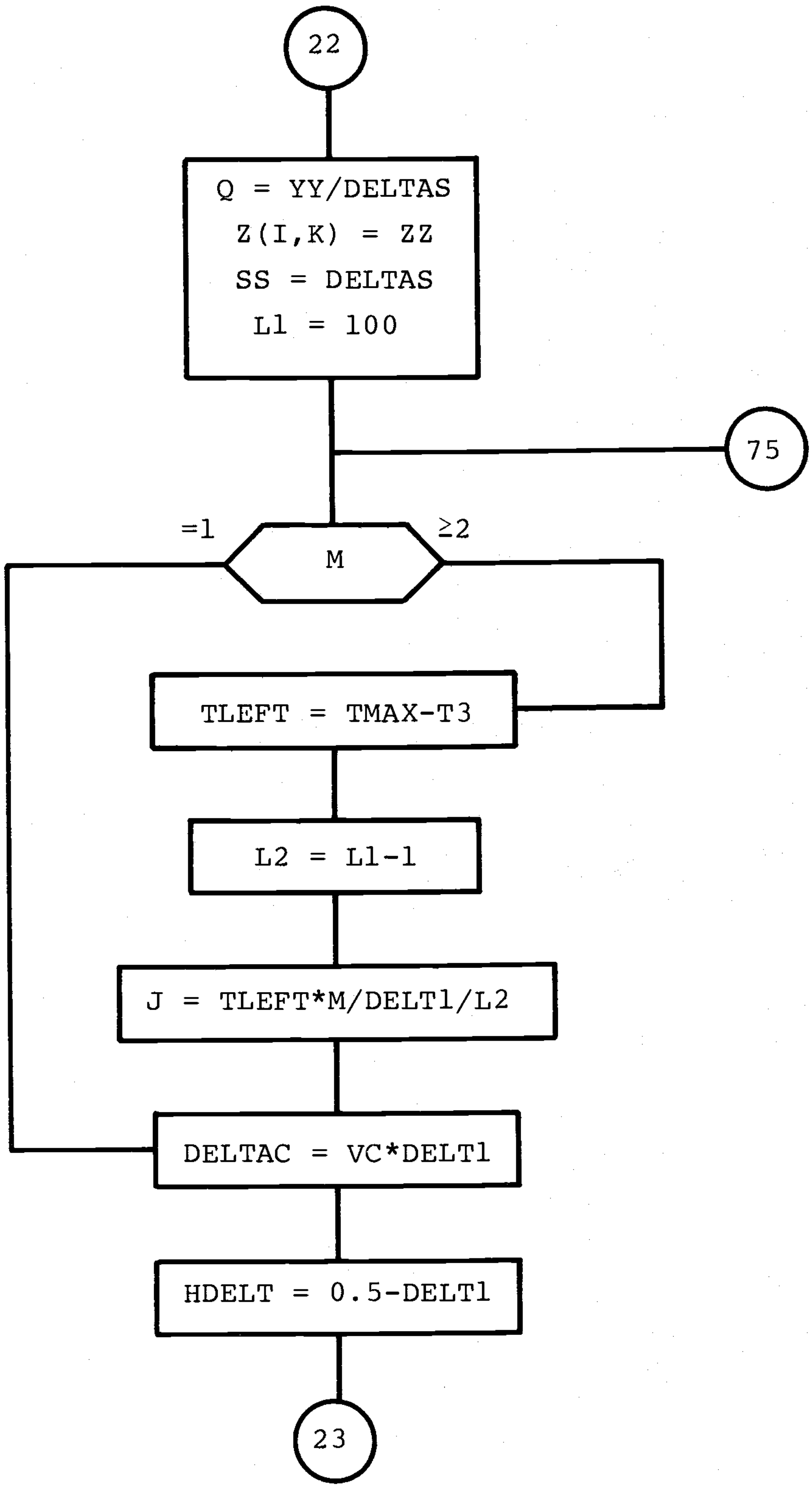
Appendix Figure 9. Flow Chart for Computer Program for Computation of Particle Trajectories.



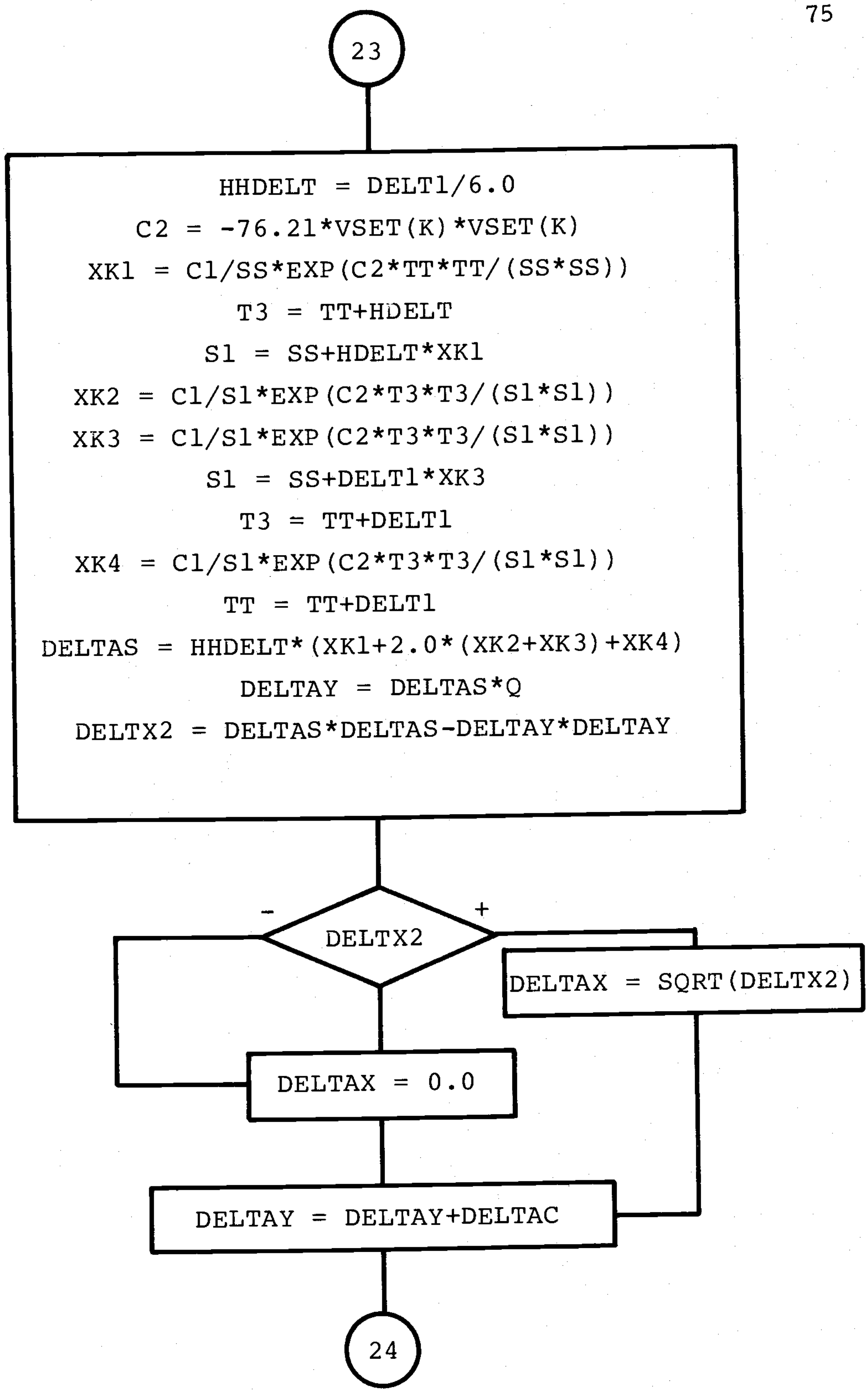
Appendix Figure 9 (continued)



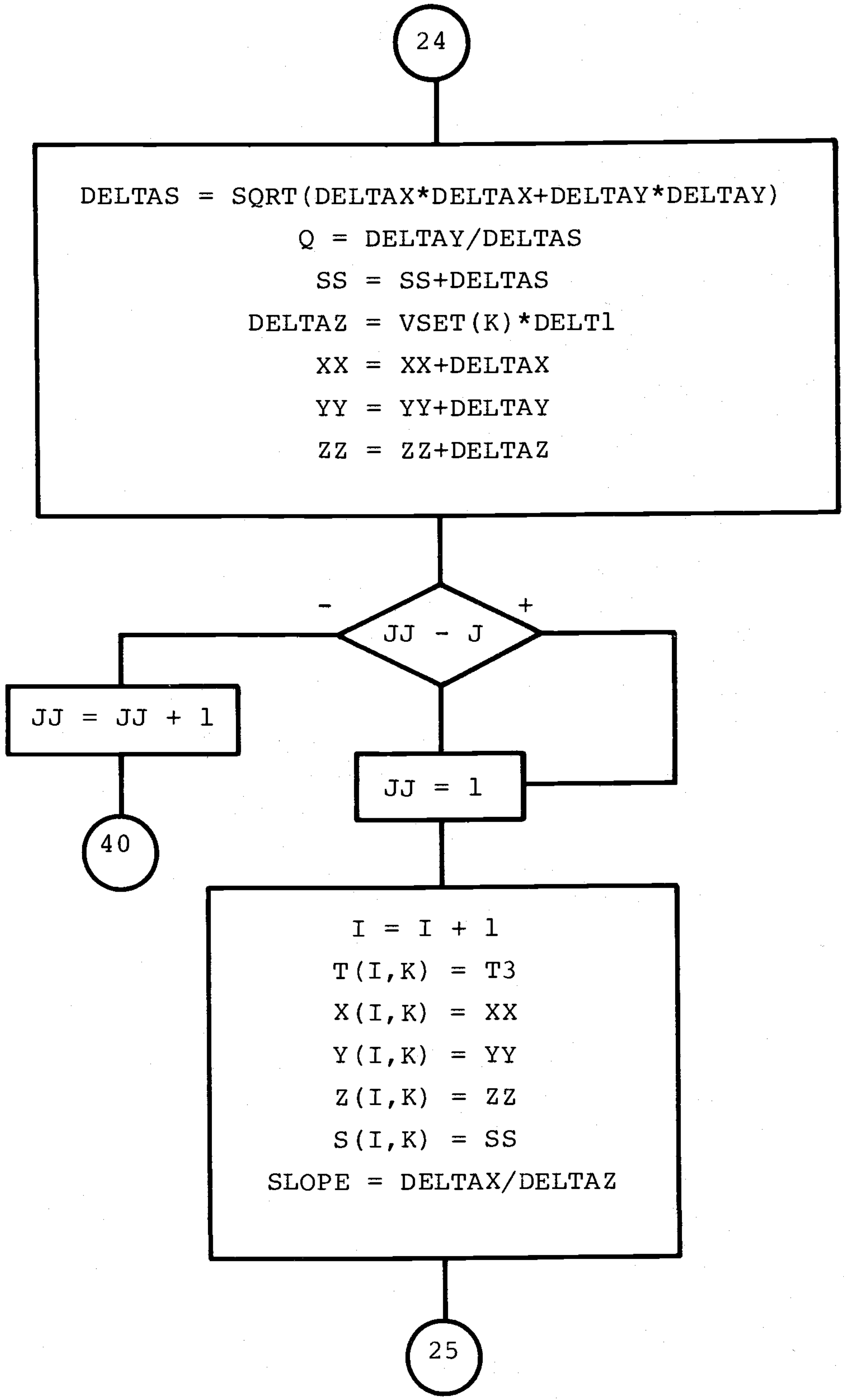
Appendix Figure 9 (continued)



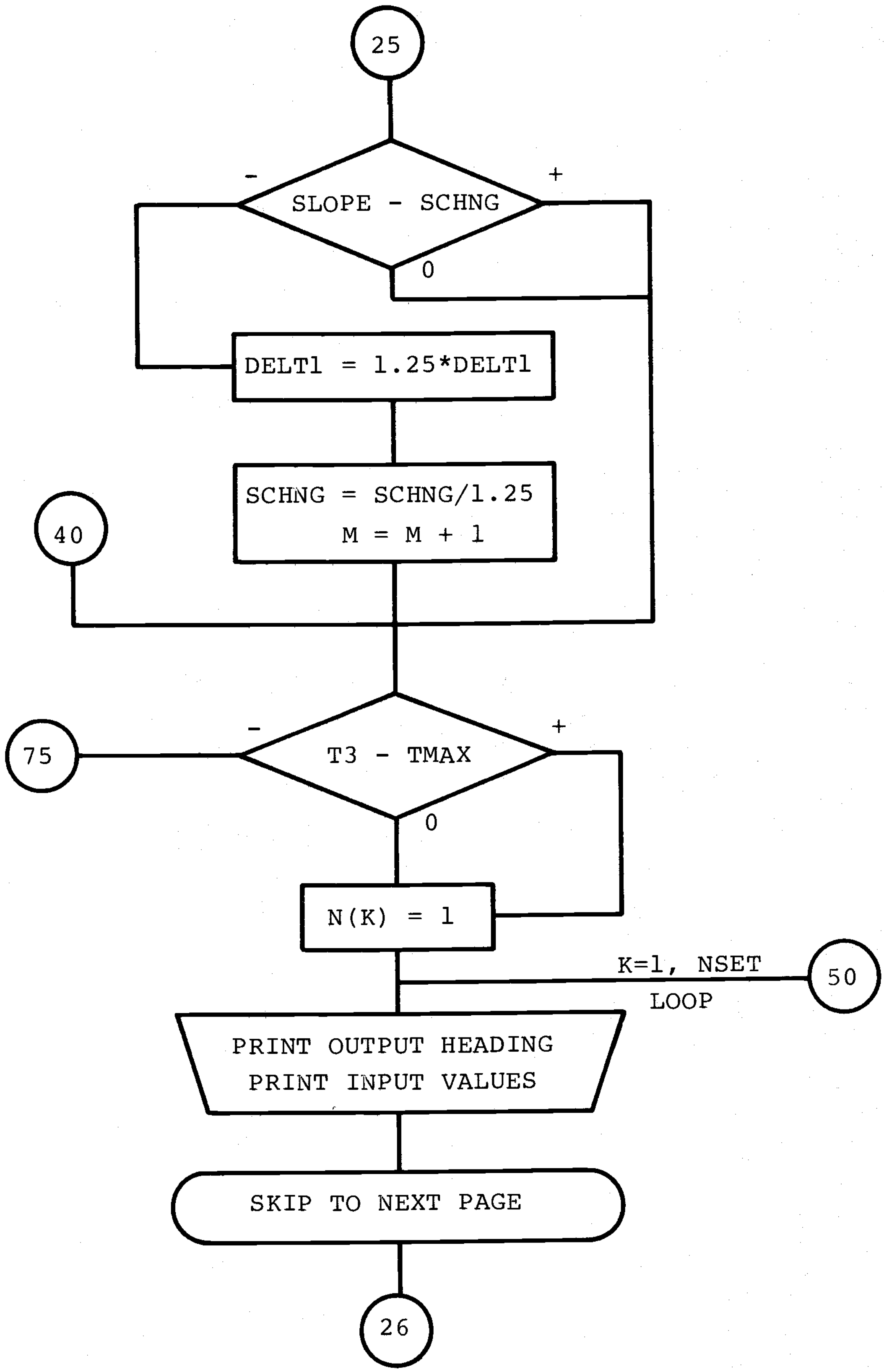
Appendix Figure 9 (continued)



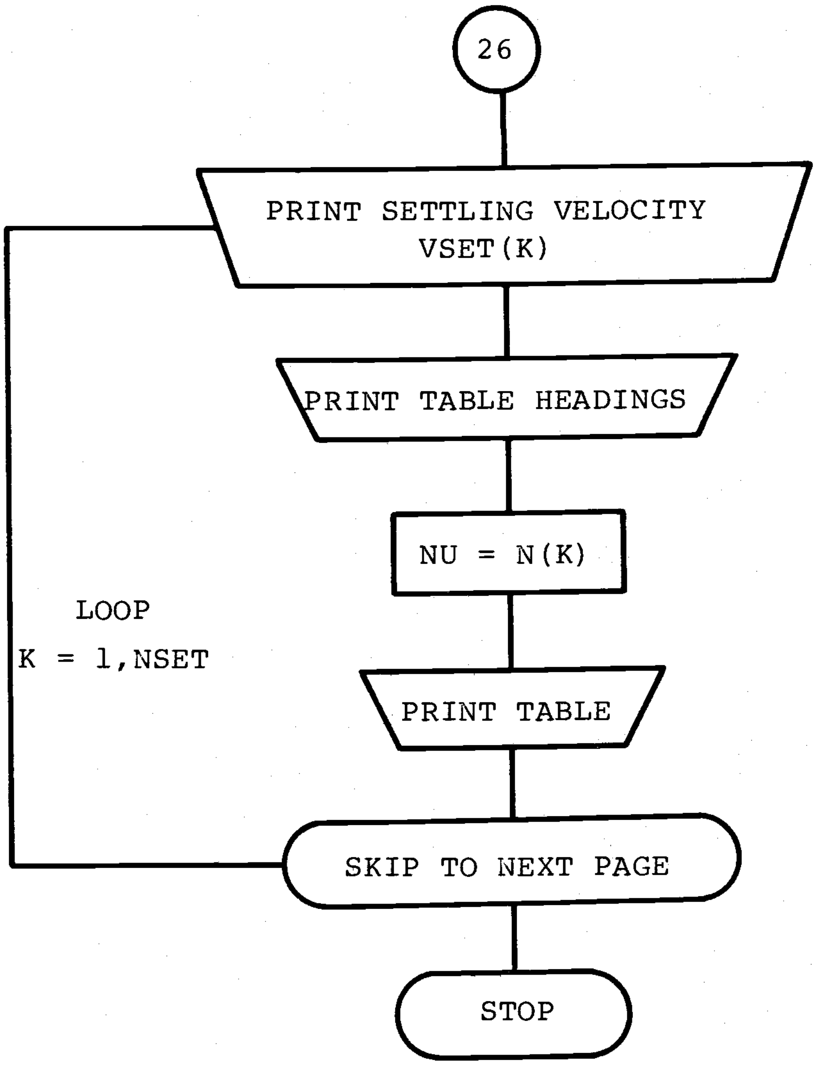
Appendix Figure 9 (continued)



Appendix Figure 9 (continued)



Appendix Figure 9 (continued)



Appendix Figure 9 (continued)