University of Washington
Department of Civil and Environmental Engineering

HYDRAULIC MODEL STUDY OF CLOSURE OF THE EAST WATERWAY DUWAMISH RIVER ESTUARY

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Water Resources Series
Technical Report No. 35
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HYDRAULIC MODEL STUDY OF CLOSURE OF THE EAST WATERWAY, DUWAMISH RIVER ESTUARY

By

Ronald E. Nece, Carl B. Tweedt and Eugene P. Richey

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Prepared for
Cornell, Howland, Hayes & Merryfield/Clair A. Hill & Associates
Bellevue, Washington

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ACKNOWLEDGEMENT

The model study reported was performed for Cornell, Howland, Hayes and Merryfield/Clair A. Hill & Associates, Bellevue, Washington. Mr. Dale King was the sponsor's chief representative on the study. Additional liaison with the sponsor throughout the investigation was provided by Mr. Joe Scott and Mr. Hugh Savage. The sponsor, in addition to providing data on the various closure schemes to be investigated in the study, arranged for an open meeting of representatives from various public agencies and user groups at which helpful information was exchanged early in the model testing program.

Mr. Fred Williams of the City of Seattle Engineering Department provided data on pier locations for proposed bridge configurations in the study area.

The study was conducted at the Charles W. Harris Hydraulics Laboratory, University of Washington. The tests were conducted by Mr. Carl B. Tweedt, graduate student, under the supervision of Professors Ronald E. Nece (Principal Investigator) and Eugene P. Richey (Co-Investigator).

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I. INTRODUCTION AND OBJECTIVES

This report presents the findings of an hydraulic model study conducted to determine the effects on river and tidal hydraulics in the Duwamish River estuary, Seattle, due to proposed modifications of the East Waterway.

The proposed modifications investigated were as follows:

(1) The partial closure of the East Channel of the Duwamish River at the eastbound (southern) span of the Spokane Street Bridge. The East Channel is the channel connecting the East Waterway and the Duwamish River.

(2) The complete closure of the East Channel between the Spokane Street Bridge and the southern tip of Harbor Island.

(3) The placement of large bridge piers in the East Channel, providing a modified partial closure of the channel.

A general location map of the study area is shown in Fig. 1. Details of the partial closure and full (complete) closure are shown in Figs. 2 and 3, respectively; the single bridge pier layout tested is indicated in Fig. 4.

Two particular effects of these proposed modifications were investigated in the model study:

(1) Changes in currents, specifically in maximum ebb flow velocites, in the West Waterway. Model tests were restricted to determination of changes in ebb flow currents in the Harbor Island Reach, as this channel is the navigation channel connecting Elliott Bay and the navigable, dredged portion of the Duwamish River known as the Duwamish Waterway.

(2) Changes in the flushing, or gross exchange, rates due primarily

to tidal motions in the East Waterway. The results of these findings were then to be applied by the sponsor in developing water quality models for the East Waterway under the various degrees of closure.

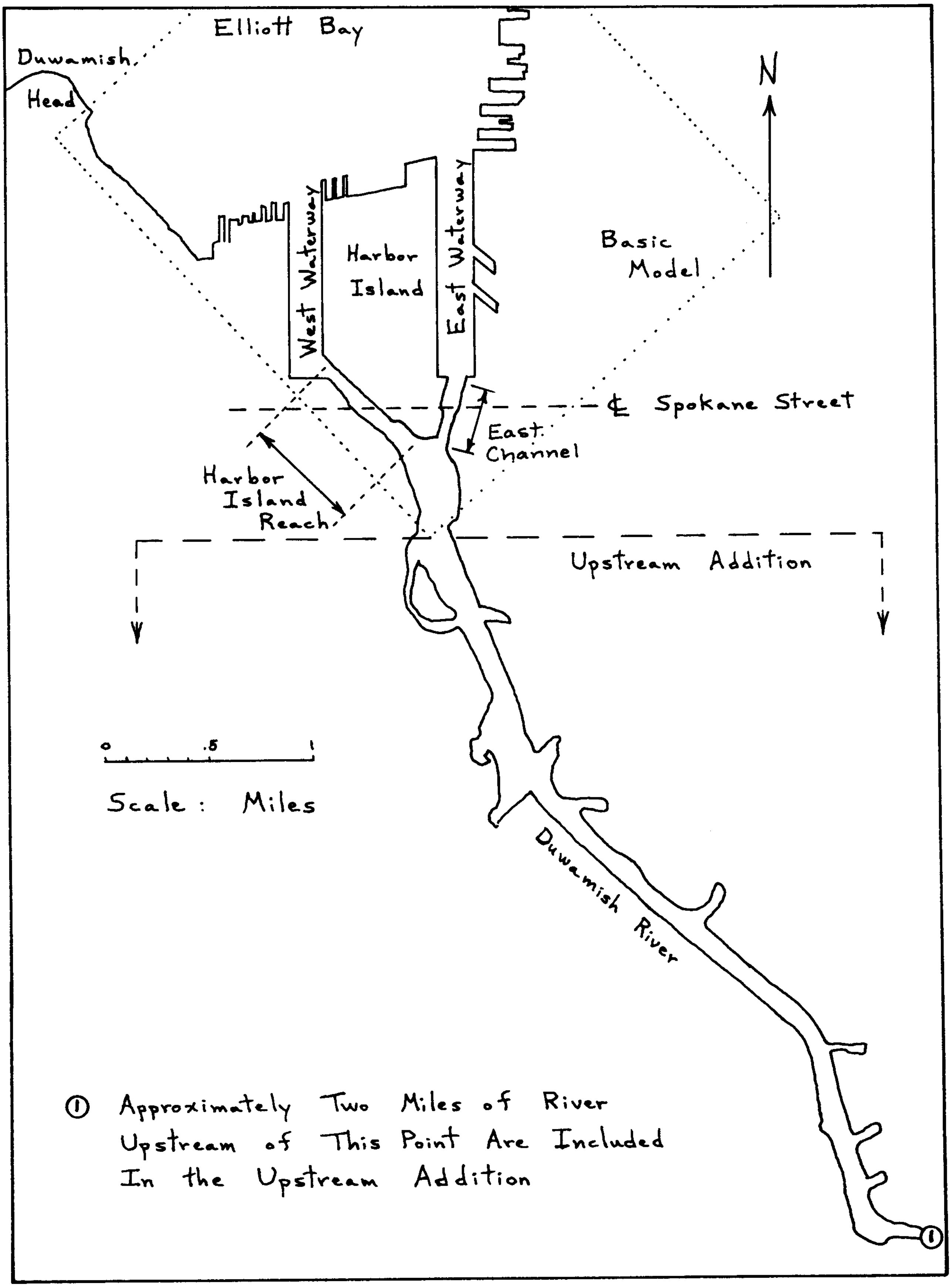

Figure 1- Definition Sketch, Model Study Area

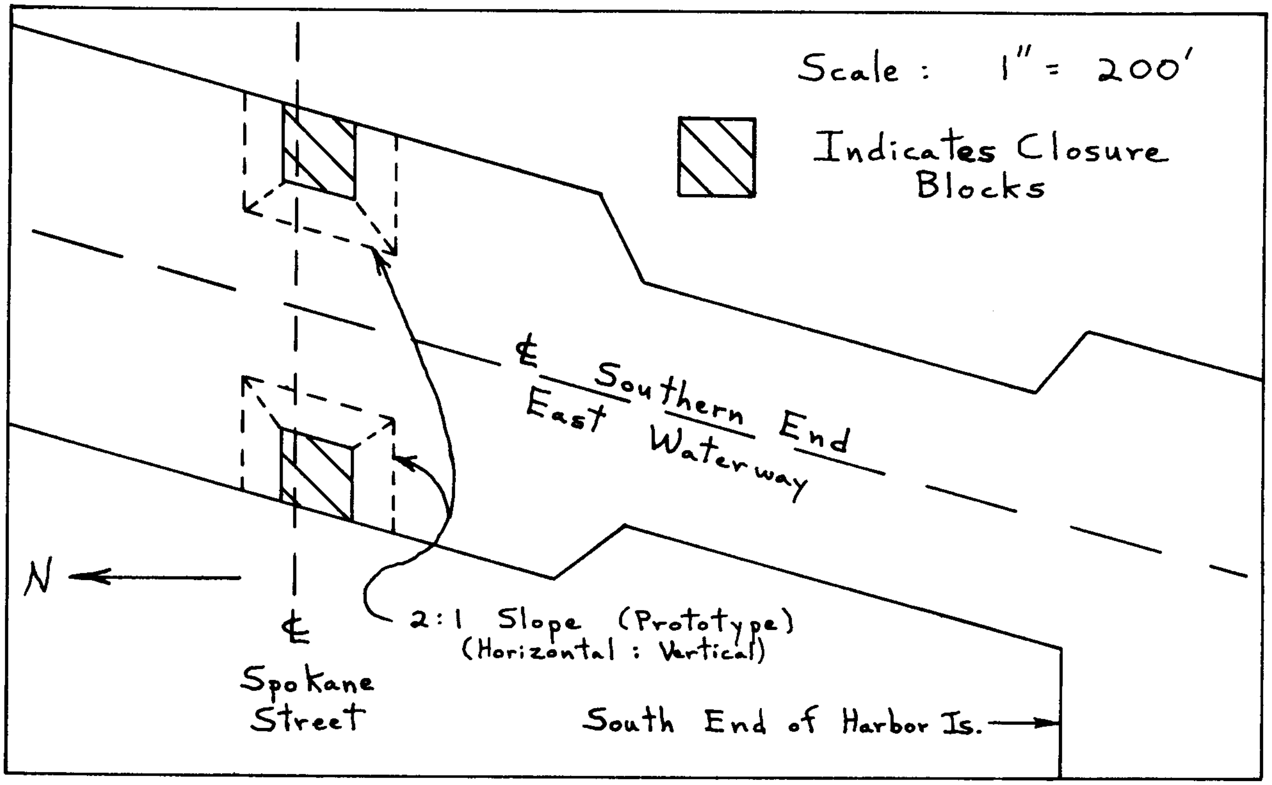

Figure 2 - Configuration of the East Waterway with Partial Closure

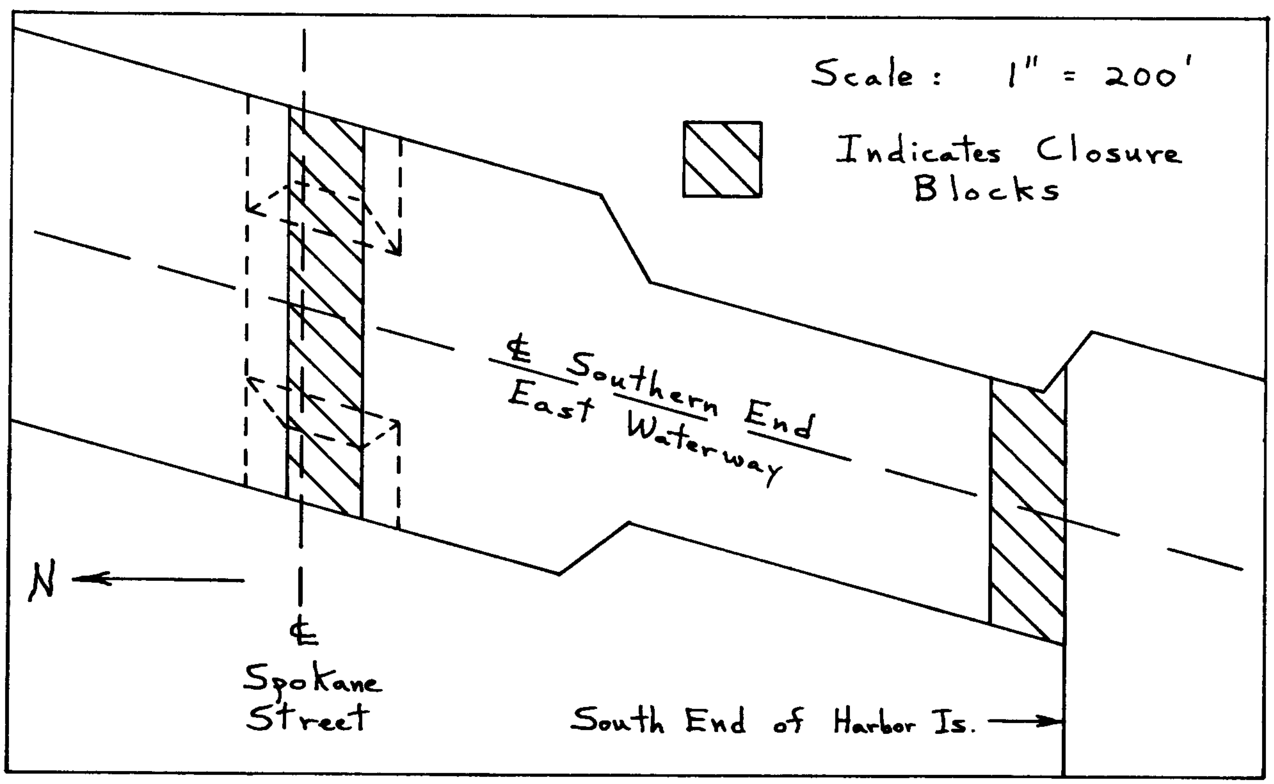

Figure 3 - Configuration of the East Waterway with Full Closure

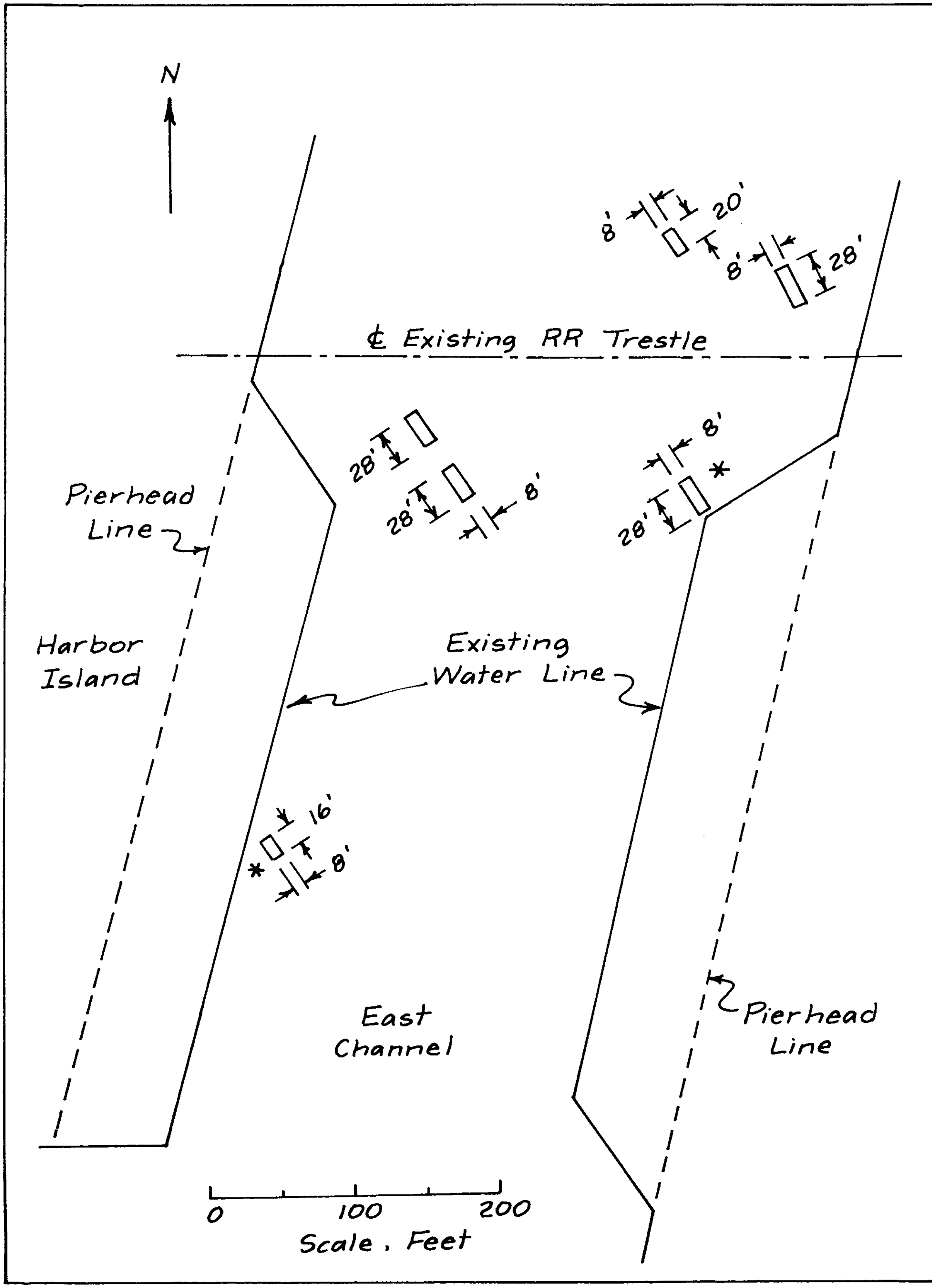

Figure 4 - Bridge Pier Locations in East Channel

II. SCOPE OF TEST PROGRAM

The combinations of field variables - tidal ranges and river inflows - used in the model tests were selected in an effort to match the need of observing the effects of the proposed channel modifications for both representative and critical extreme conditions in the prototype with physical limits of the model and with time available for the testing program.

Tides in Puget Sound are of the strongly mixed type, with unequal flows. The mean tide level in Elliott Bay is 6.6 feet above MLLW (datum); the mean tide is 7.6 feet, and the average diurnal tide is 11.3 feet, as tabulated by the United States Department of Commerce, Coast and Geodetic Survey (1970). Record high and low tides on Elliott Bay are 14.6 and -4.7 feet, respectively. Diurnal inequalities of the tides are illustrated in Fig. 5.

The tidal curve generated in the model tank was limited to a sinusoid. All model test runs were made at a prototype semi-diurnal tidal period of 12.4 hours, and all runs were made with MWL at the 6.6-foot elevation. Three tidal conditions were modeled. The high tidal range selected was 14.0 feet;

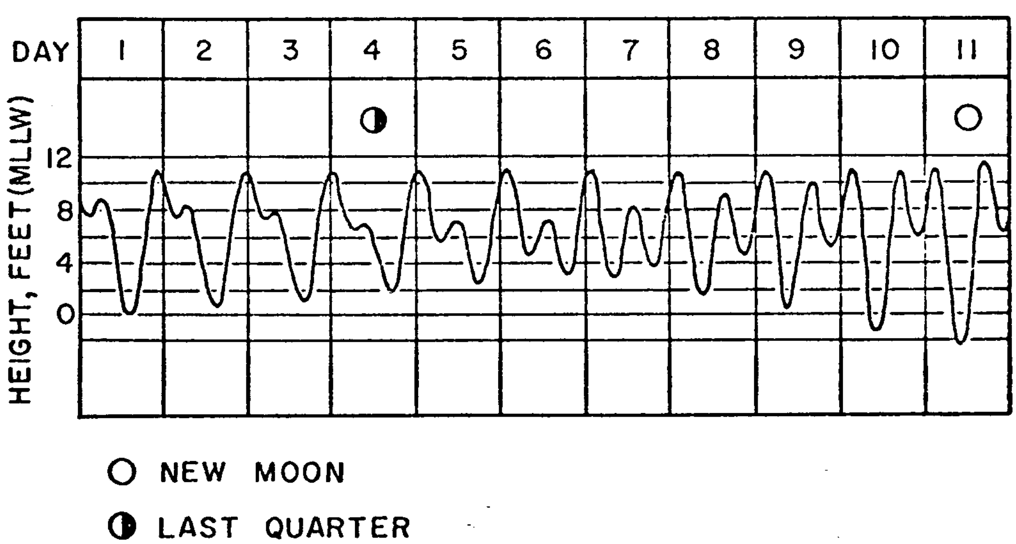

Figure 5 - Example of Strongly Mixed Tides, Seattle

this is a representative spring tide, and also could be used for model verification since some limited field data had been taken at this range. The low tidal range selected was 3.0 feet; this was considered to be the lower limit of the model for similarity of prototype behavior, as well as being a representative 'low' for Seattle. The third was the mean tidal range of 7.6 feet.

Freshwater inflow from the Duwamish River also was limited to three equivalent prototype discharges in the model study. The high river flow tested was 7,300 cfs. This is less than the maximum discharge of record, since the Howard A. Hanson Dam became operational on the upper Green River, of 12,100 cfs; it is representative, however, of peak flows which might be exceeded only a few times each winter. The low river flow tested was 300 cfs, a typical summer low flow; the minimum flow of record is 195 cfs. The third discharge used was a mean flow of 1,500 cfs, used to represent average conditions. This mean value approximated the 1,491 cfs which is the average daily discharge for the published 11 years of record from the gaging station at Tukwila, at river mile 12.4 on the Green-Duwamish River, as listed by the United States Department of the Interior, Geological Survey (1971).

Only four of the nine possible tidal range-river flow combinations were tested. These are listed in Table I.

The high tidal range - high river flow (HH) combination was used for both initial verification of the model and for the velocity measurements in the Harbor Island Reach because it was the worst combination from the standpoint of navigation.

All four combinations were used to study the flushing characteristics of the East Waterway. The low tidal range - low river flow (LL) combination

Table I

Tidal Range - River Flow Combinations Tested

Test Combination	Tidal Range	River Flow
1. HH	High -- 14.0 Feet	High -- 7,300 cfs
2. MM	Mean -- 7.6 Feet	Mean -- 1,500 cfs
3. ML	Mean -- 7.6 Feet	Low -- 300 cfs
4 LL	Low -- 3.0 Feet	Low -- 300 cfs

was the worst possible for estuary flushing. However, due to the diurnal inequality of the prototype tide curve as shown in Fig. 5, successive low tide water surface elevations will not be the same and the effective prototype estuary flushing will be greater than that predicted by the repetitive equal tides of the model. The mean tidal range - low river flow (ML) combination was considered to be representative of the more critical summer conditions which could have significant effect on water quality in the estuary and in the East Waterway in particular.

Emphasis in the East Waterway flushing tests was placed on the effects of partial and full closure of the East Channel. Only one test, at the ML combination, was made with the bridge piers shown in Fig. 4 placed in the East Channel. This test confirmed the expectation that the effects of the bridge piers were bracketed by results for the various degree of closure tests, hence no further tests were required.

III. MODEL DETAILS

Model Scale

In the initial design of the model it was decided that for proper simulation of prototype behavior the model should include the portion of Elliott Bay lying south of Duwamish Head, the complete East and West Waterways, and a short section of the Duwamish River upstream of the two waterways. In order to fit this area within the 8-foot by 10-foot working section of the laboratory tidal basin described below, a horizontal scale ratio of 1:1,500 was required. The area incorporated within the model basin is shown on Fig. 1.

Vertical distortion was required in the model for two reasons:

(1) An undistorted model with the small 1:1,500 scale would make measurements of water surface displacements (tidal elevation changes) very difficult to measure.

(2) Viscous effects associated with the extremely small depths and velocities in an undistorted model could lead to non-realistic current patterns in the model.

A vertical distortion of 10 was selected; this is a common distortion ratio, and is considered as appropriate for tidal models by the American Society of Civil Engineers (1942).

Scale distortion removes a model from producing dynamic similarity with the prototype. The model was constructed and operated in the conventional manner to conform with Froude law criteria for distorted models, in which gross kinematic similarity was obtained. The model ratios used in this study are listed in Table II.

An addition to the basic model was a section constructed outside of the model basin and which duplicated a 6.25-mile reach of the Duwamish River upstream of the main study area but subject to tidal effects and containing a significant fraction of the estuary tidal prism volume. This addition, using simplified rectangular cross-sections over appropriate equivalent prototype lengths arranged in a labyrinth form to conserve floor space, was then connected to the Duwamish River section in the model basin by siphons.

Table II

Model Ratios

Distortion (vertical:horizontal)		1:10
Length, horizontal	X_R	1:1,500
Length, vertical	Z_R	1:150
Area, horizontal	$A_x = X_R^2$	1:2,250,000
Area, vertical	$A_z = X_R Z_R$	1:225,000
Volume	$Vol_R = X_R^2 Z_R$	1:337,500,000
Velocity	$Vel_R = Z_R^{1/2}$	1:12.25
Discharge	$Q_R = X_R Z_R^{3/2}$	1:2,740,000
Time	$T_R = X_R / Z_R^{1/2}$	1:122.5

The model time period used and corresponding to a 12.4-hour prototype semi-diurnal tidal period was 6 minutes 4 seconds.

Model Construction

The model was built in accordance with aerial photographs and sounding data from the Seattle District, Corps of Engineers. Pier plans and additional sounding data from the Port of Seattle Commission, and a U.S. Coast and Geodetic Survey chart of the Seattle Harbor and Duwamish Waterways for plan view and depth information on Elliott Bay were also used.

A simplified cross-section was used for both the East and West Waterways. The simplified shape and the prototype cross-section, shown by solid and dashed lines respectively on Fig. 6, have equal cross-sectional water areas. The southern end of the East Waterway, the Harbor Island Reach, and the upper Duwamish River were constructed in the model with vertical walls along Pierhead Lines. This was considered a valid distorted model approximation of shoaled, irregular shorelines parallel to a dredged waterway. Both Waterways were constructed with straight walls except for the two large slips which were built into the east side of the East Waterway.

All planar surfaces in the model were made from 1/4-inch exterior plywood. Channel bottoms were built up with wood blocks and then contoured with sand-cement plaster to duplicate the bottom sounding data from the prototype. Caulking compound and wood filler compounds were used to fill cracks and construct more detailed areas. Sealant was applied to all wood surfaces prior to painting. The model rested on a wood frame which brought the MWL of the model within the working range of water levels within the tidal basin; the model was leveled by matching three vertical control points at MWL in the model with mean water surface level in the tidal tank. Aprons were added to the basic model once it was in the tidal tank so that the effects of adjacent shoreline and bottom contours in Elliott Bay could be accounted for in the model.

Overall views of the model and tidal basin are given in Figs. 7 and 8. The exterior addition of the Duwamish River reach is in the background in each photograph. In Fig. 8, a view from the north, the (model) temporary dams used in the flushing rate tests are shown in place at each end of the East Waterway.

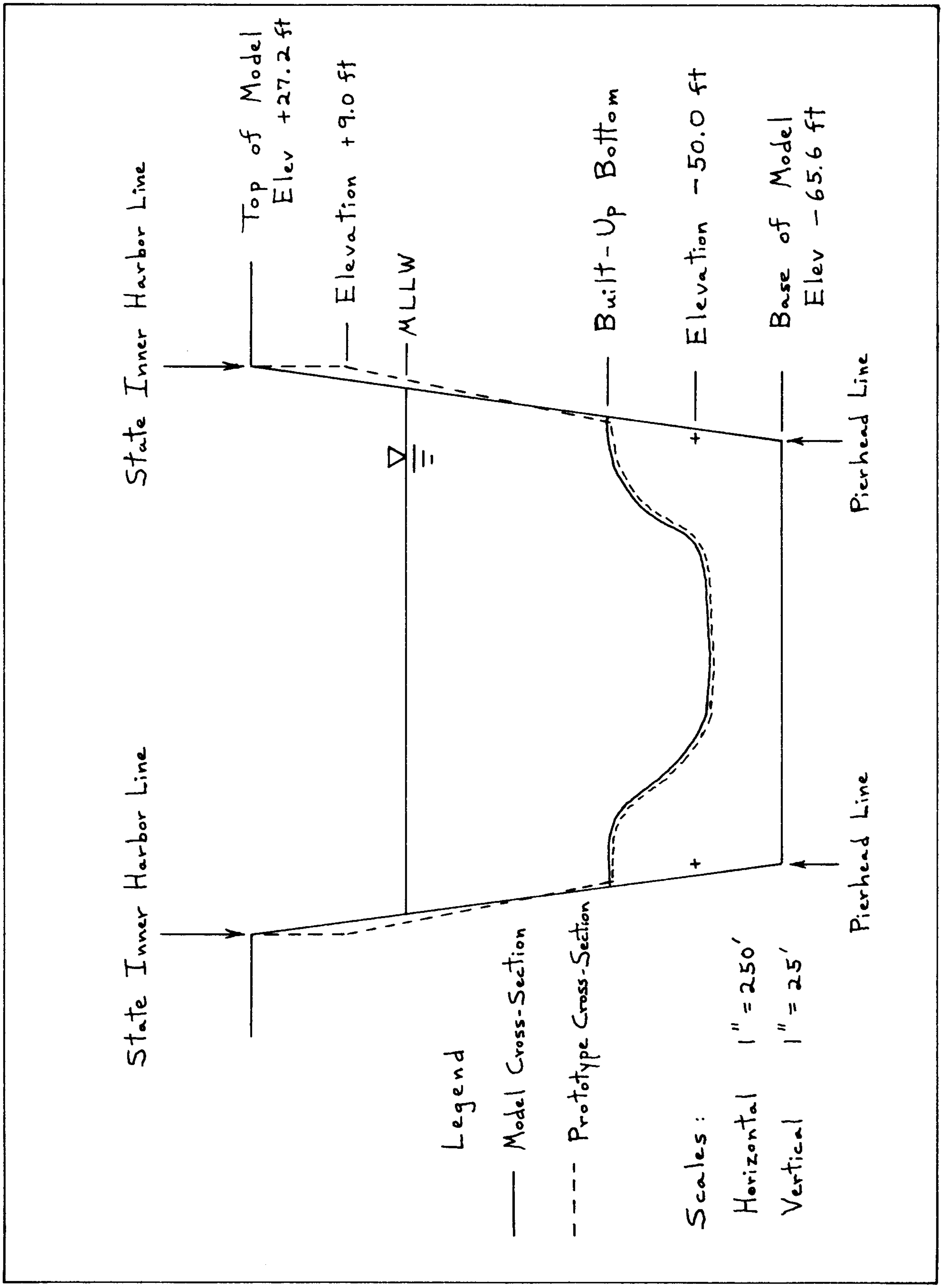

Figure 6 Waterway Cross-Sections of Model and Prototype

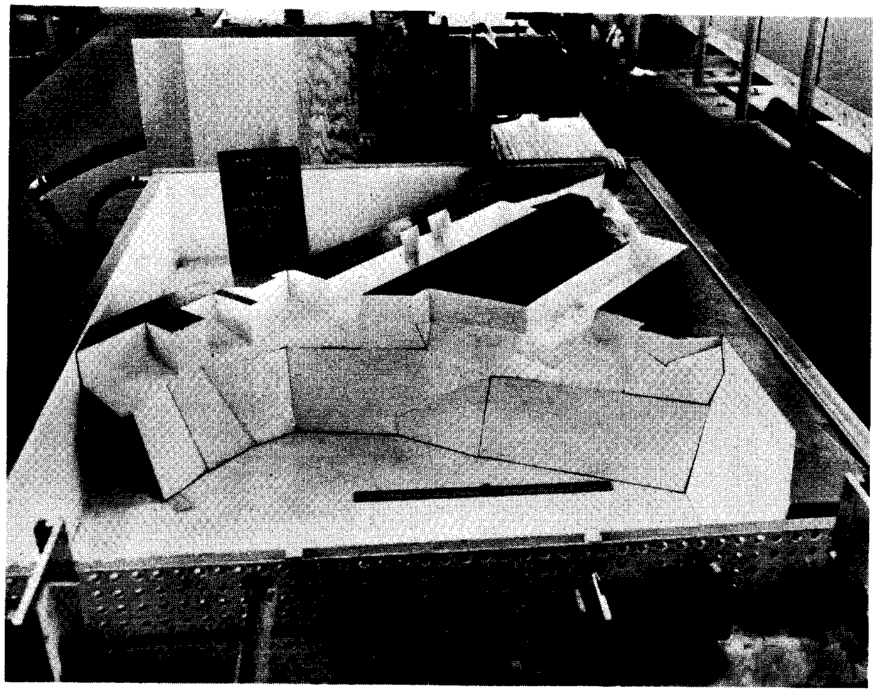

Figure 7 - Overall View of Model and Testing Basin

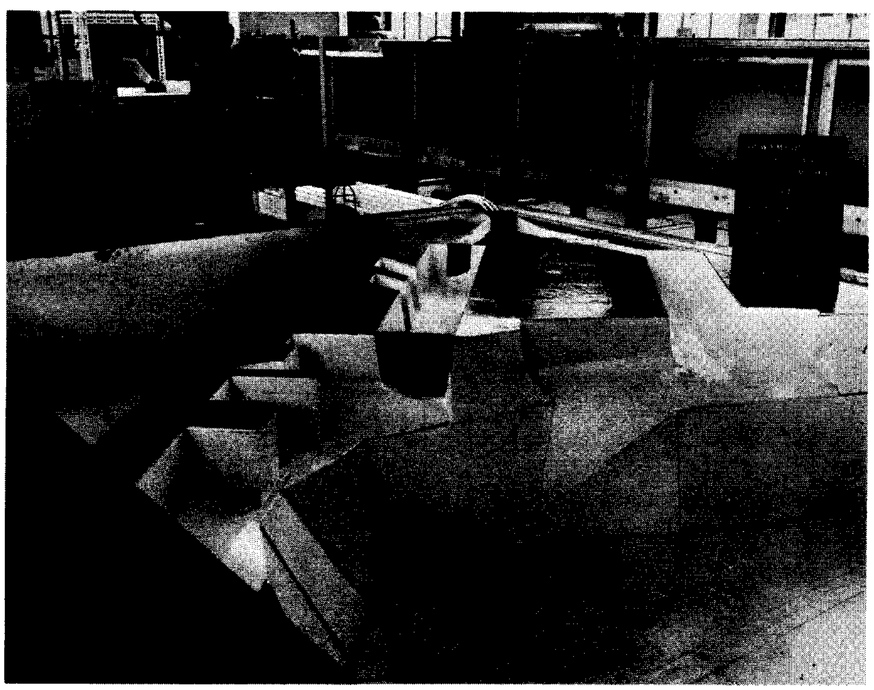

Figure 8 - View from North, with Temporary Dams Used for Flushing Tests in the East Waterway

Small wooden blocks were fabricated to simulate the East Channel closure modifications shown on Figs. 2 and 3. A scaled plexiglass reproduction of the west Spokane Street Bridge piers was placed in the Harbor Island Reach. No attempt was made to simulate the numerous but small (16-inch diameter) pilings of the existing Spokane Street Bridge over the East Channel as it was felt that the bridge pilings have little effect on the gross flow characteristics in the East Channel. Figures 9(a), 9(b) and 9(c), respectively, show the model arrangements for the existing, partial closure, and full closure configurations of the East Channel. In these photographs, taken from the south, the pier configuration of the twin-span west Spokane Street Bridge is visible.

Tidal Basin

The tidal basin has an overall plan size of 8 feet by 12 feet, with an 18-inch working depth. The constant amplitude, constant period tides of the model test were produced by a tidal generator which was a variable-elevation waste weir, driven by a small motor through appropriate gear reducers and a Scotch yoke mechanism to obtain harmonic motion, and fed by a constant-rate water supply. The variable speed gear box and adjustable cam pins on the Scotch yoke assemblies provide adjustment of the tidal period and range, respectively; mean water level adjustment is provided by threaded rods connecting the weir to the Scotch yoke assemblies. The tank, tide generator, and closed circuit system for pumping water into the tank and over the weir are shown schematically in Fig. 10. Tidal periods were set by use of a stop watch. A non-recording tide gage provided an accurate, visual reading of the water surface level within the tank during a tidal cycle. Further details of the tide generator, which has been verified to produce very nearly sinusoidal

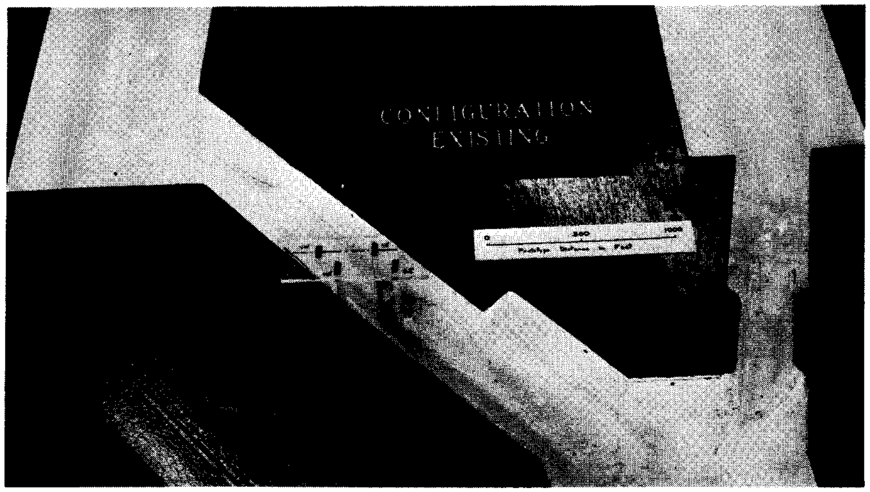

Figure 9(a) - Model Set-up, Existing Configuration,
East Channel

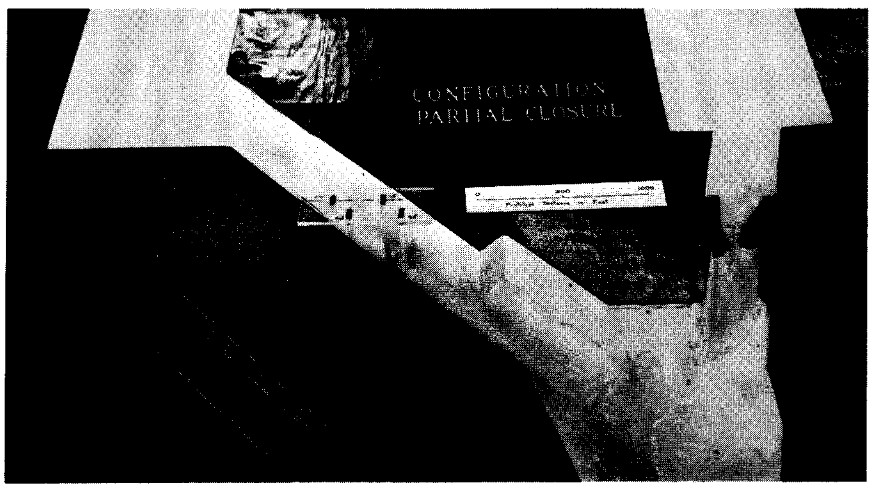

Figure 9(b) - Model Set-up, Partial Closure,
East Channel

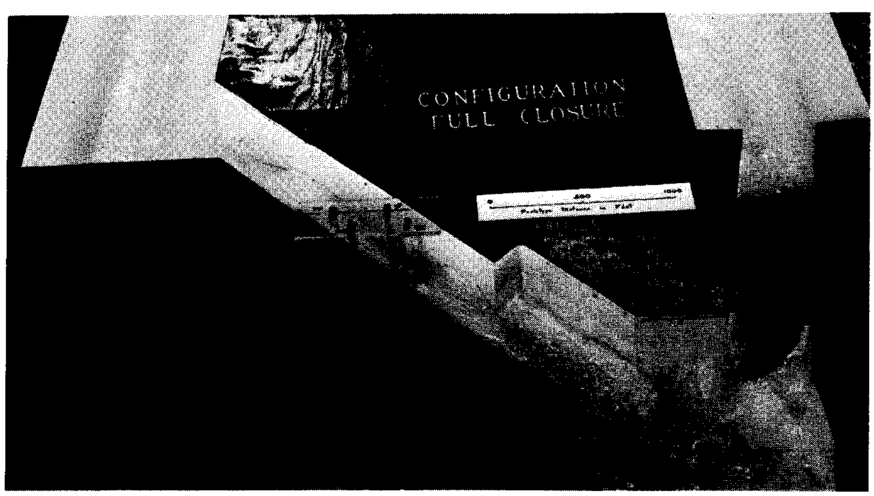

Figure 9(c) - Model Set-up, Full Closure,
East Channel

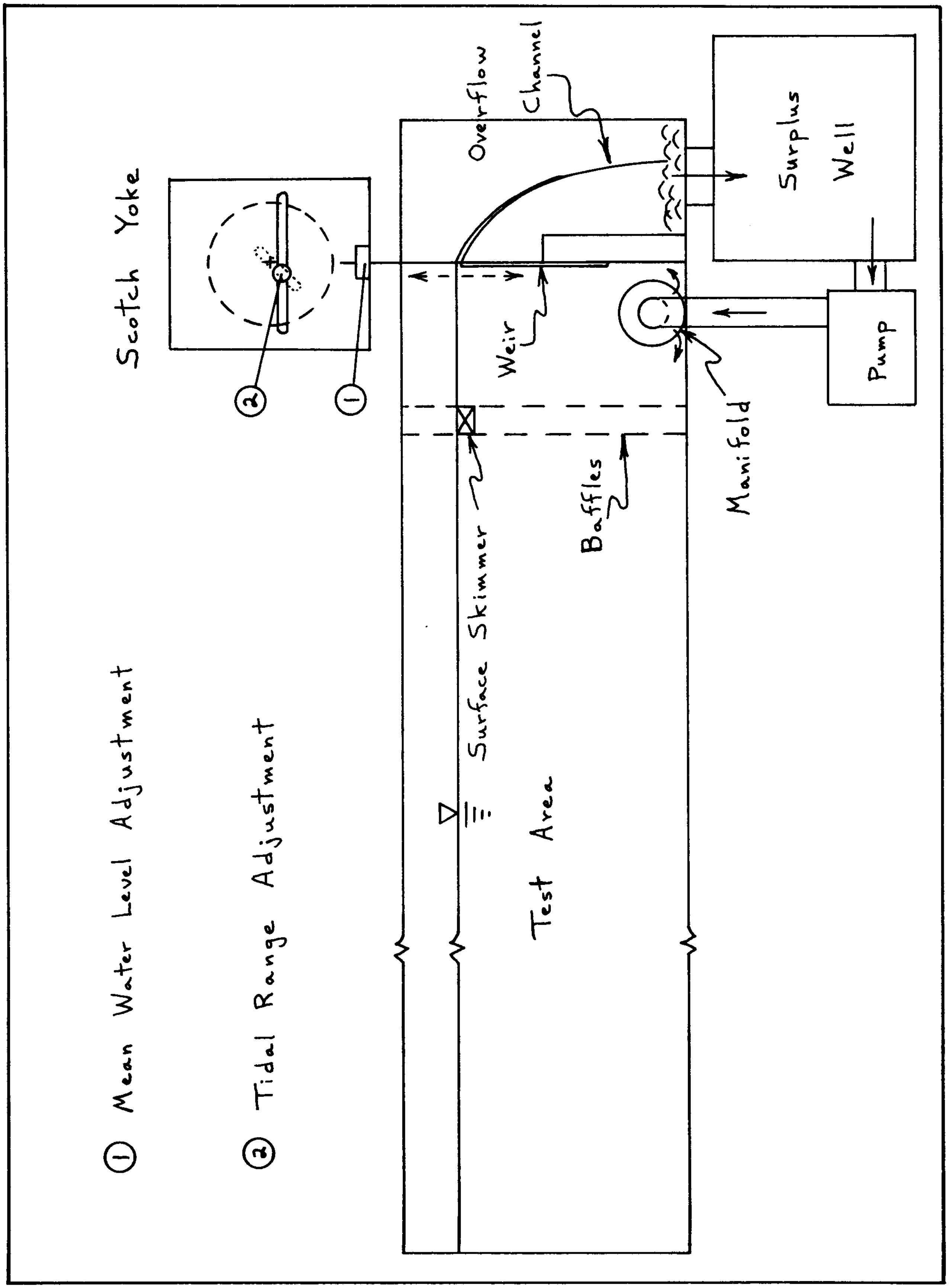

Figure 10 - Schematic Drawing of the Tidal Tank and Closed Fluid System

tides, have been given by Lewis (1972).

Valve-regulated freshwater inflows to the study area from the Duwamish River were introduced into the upstream end of the exterior 6.25-mile (prototype equivalent) reach of river. River discharge rates were measured with an orifice meter calibrated in place; interchangeable orifice plates of 3/32-inch and 1/4-inch opening size were used in the 1-1/4-inch supply pipe in order to cover the range of river flows tested.

Model Limitations

Two limitations inherent in such a small-scale, single-fluid model were recognized before the study was begun and had to be remembered throughout.

The use of a single fluid (fresh water) in the model eliminates the possibility that the model can reproduce details of the two-fluid (fresh water and salt water) situation in the prototype estuary. Further, as has been shown by Harleman (1966), it is not possible to obtain concentration similitude in single-fluid, distorted models. Therefore, the model could not be used to obtain any close-grained, detailed predictions of diffusion behavior in the estuary.

Despite the vertical distortion, Reynolds numbers in the model still are low and as a consequence detailed local velocity patterns will not scale exactly between model and prototype. In an earlier study using the same model basin and testing procedures used in the present study, Nece and Richey (1972) have shown on the basis of some field measurements that the small-scale model does give quite accurate values of the depth-integrated velocity vector at a station in tidal model where two-fluid effects are either negligible or not present.

It was concluded that these limitations would not affect the primary objectives of the present model study. These points are considered further in the 'Conclusions' section.

IV. EXPERIMENTAL PROCEDURES

Velocity Measurements, Harbor Island Reach

Model currents were measured using a simple visual method. Small, 0.10-inch diameter plastic-coated drinking straws, sealed and weighted at the bottom but open at the top and cut to the appropriate length, acted as drogues responding to an effective average velocity over the water column. A typical equivalent prototype penetration for a drogue was 25 feet; longer lengths encountered grounding problems at low tide conditions. Drogue locations were plotted at discrete time intervals by marking pen on a horizontal plexiglass sheet laid over the model area under study; the requirement that an observer sight down the open vertical bore of the straw cylinder was an effective method of reducing parallax errors. The local, instantaneous velocity was determined from the measured drogue travel distance during a known time increment.

All velocity measurements were taken in the Harbor Island Reach of the West Waterway at the high tidal range-high river discharge condition. Velocites were measured only during the ebb tide flows, because highest currents are produced then, and at two particular locations. The west Spokane Street Bridge site was used for model verification measurements, as discussed in the "Experimental Results" section. Emphasis was placed on measurements off the southwest corner of Harbor Island, where the Harbor Island Reach enters the main West Waterway. Conversation with tugboat skippers isolated this particular point as the worst problem area from a navigation standpoint, because upstream ship traffic must make a turn there and contend with the higher velocities in the reach during the maneuver. This point is at Corps of Engineers River Mile 0.0. It is identified on Fig. 11 as station x = - 600;

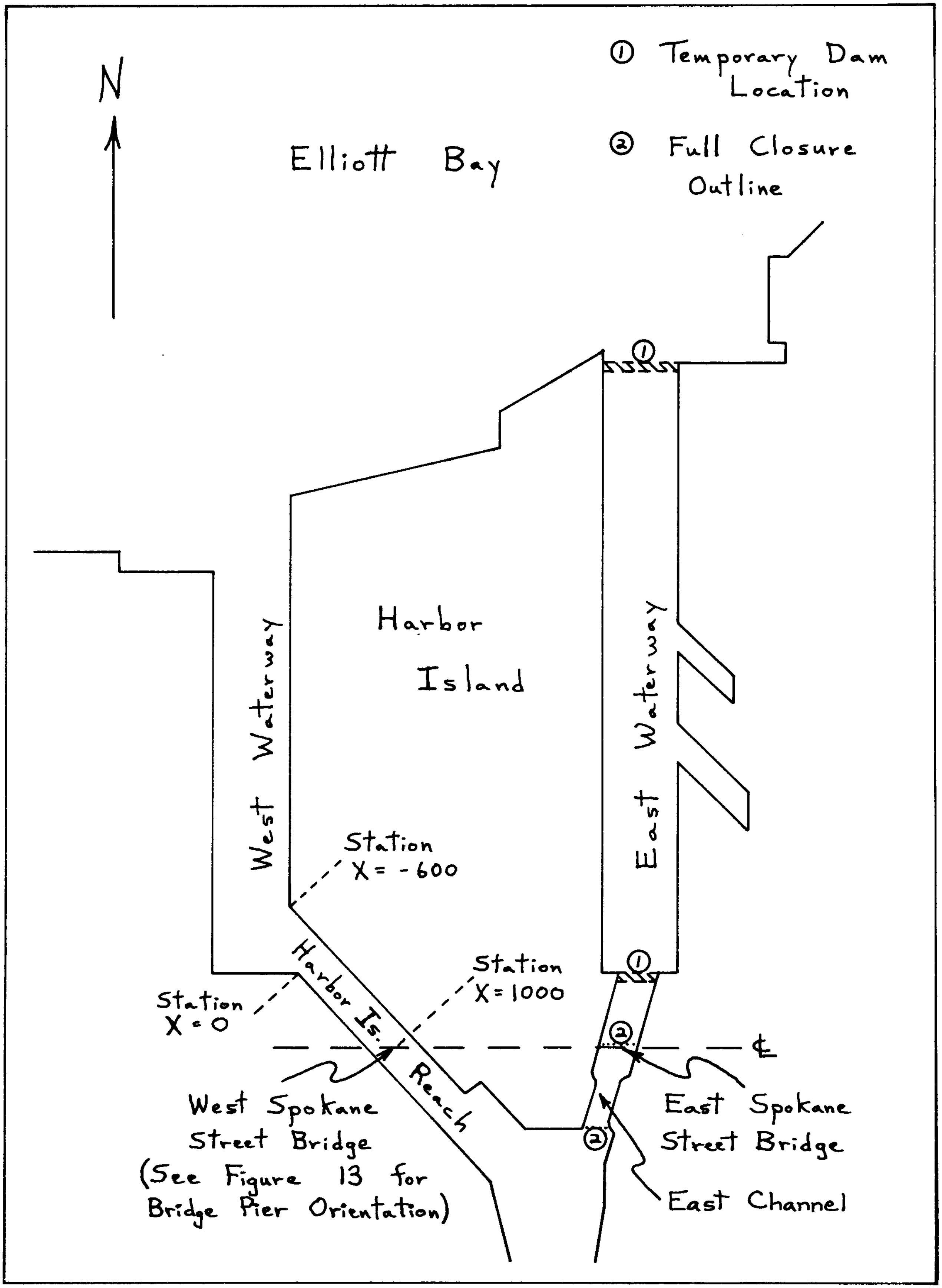

Figure 11 - Definition Sketch, Model Velocity and Flushing Areas

this arbitrary (prototype equivalent, feet) stationing used the center of the West Spokane Street Bridge as station x = 1000.

Repetitive runs were made for different time intervals during the ebb tide flow so that the variation of velocity with time, hence maximum velocity during the ebb flow, could be determined at the two locations cited.

In the velocity measurements, a drogue was inserted at the southern end of the Harbor Island Reach so it would pass by the location under study during a specific interval on the tidal curve. Drogue locations through the reach were plotted on the plexiglass overlay at 1-second intervals, a two-person operation. The scale ratios of Table II were used to determine equivalent prototype velocities at each time increment mean location in the test reach. A curve was constructed to obtain the velocity vs. position at a known time relationship for each drogue. The velocities and times (after high water slack) determined from the above curves were used to construct curves showing velocity variation with time at each of the two particular points of interest. This procedure was followed for each of the three basic East Channel configurations - existing, partial closure, and full closure.

Flushing Measurements, East Waterway

Flushing characteristics of the East Waterway were determined with the use of rhodamine-B, a conservative, fluorescent tracer dye whose relative fluorescence is an index of its concentration. Changes in the spatial average dye concentration in the East Waterway over a number of tidal cycles allowed the flushing rate of the waterway with adjacent Elliott Bay water to be determined.

Dye concentrations were measured with a Turner Model 110 flurometer. As has been indicated by Feuerstein and Selleck (1963), the fluorescence of rhodamine-B is temperature sensitive, and the dye has a photochemical decay when exposed to bright sunlight. Accordingly, all dye samples withdrawn from the model during a test were stored overnight in a closed container so they would come to temperature equilibrium with the ambient air before their concentrations were read, and no model tests were performed when the basin was subject to direct sunlight.

The following steps were followed in each flushing test.

(1) The basin and surplus well, initially empty, were filled with fresh water from the city system.

(2) The tidal range and river flow were set, with the desired configuration of the East Channel in place.

(3) The model was run through at least one tidal cycle to dampen out any residual currents from the basin filling operation.

(4) The tide generator was stopped at high water slack, and the East Waterway was isolated from the rest of the model by temporary dams placed at the north and south ends of the waterway. (See Figs. 8 and 11).

(5) A blank reagent sample was withdrawn from the East Waterway to serve as the 'zero' reference for concentration measurements.

(6) 40 cc of rhodamine-B dye initially diluted 1:4000 were added to the East Water by syringe, and distributed over space as evenly as possible.

(7) The solution was stirred mechanically to achieve uniform mixing, and 13 samples were withdrawn at equidistant spacings along the waterway centerline. The mean value of these samples was taken as the initial spatial average dye concentration, C_o, for the flushing test.

(8) After disturbances associated with mixing and sampling in the East

Waterway had died out, the temporary dams were removed gently and the tide generator restarted.

(9) After five tidal cycles the generator was again stopped at high water slack, the temporary dams reinserted, the solution in the waterway remixed, and 7 samples were withdrawn at equidistant spacings along the waterway centerline.

(10) The tidal tank and surplus well were drained to remove the dye injected during the run, in preparation for the next run.

(11) The reagent blank, initial samples, and final samples were stored for the later fluorometer readings indicated above.

Earlier tests by Lewis (1972), in which run durations of different numbers of cycles had been compared, had established that the 5-cycle operation was long enough so that per-cycle values calculated on the basis of the final sample concentrations could be considered as truly representative of one-cycle behavior. The large number of initial samples was selected on the basis of preliminary tests in order to get a satisfactory initial average concentration. The rectangular planform of the East Waterway, and the two slips on its east side, made it difficult to obtain uniform mixing throughout; the mixing and sampling procedures used decreased the sample concentration difference to less than 10 percent from the mean, considered adequate for the purposes of the test. Fewer samples were needed at the end of the run because of the mixing which had taken place during the run; the differences of the final 7 samples also were less than 10 percent of their mean.

The waterway flushing rate was derived from an average per cycle retention coefficient which was the ratio of the spatial average dye concentration in the waterway at the end of a tidal cycle (high water slack) to the spatial average dye concentration at the beginning of the same cycle. Because the method uses gross spatial averages and not local values, the need for care in establishing the initial conditions is evident.

The average per cycle exchange coefficient, which indicates the proportion of the water in the waterway which is exchanged (flushed out of) with the ambient Elliott Bay water during each tidal cycle is defined by the equations

$$E = 1 - R \tag{1}$$

and

$$R = \left(\frac{C_o}{C_i}\right)^{1/i} \tag{2}$$

where: E = average, per cycle, exchange coefficient

R = average, per cycle, retention coefficient

C_o = initial spatial average concentration

C_i = spatial average concentration after i cycles (high water slack to high water slack = 1 cycle)

Equation (2) is obtained as follows:

Let $C_1 = RC_o$

Let $C_2 = RC_1 = R(RC_o)$, etc.

Therefore $C_2 = R^2C_o$

and $C_i = R^iC_o$

V. EXPERIMENTAL RESULTS

Model Verification

The first step in obtaining results from the model tests was to insure that the model reproduced known prototype behavior. Existing field data suitable for verification of the model were limited. Prototype velocites in the Harbor Island Reach at the west Spokane Street Bridge reported by Longfield (1971) were considred to be the most appropriate data for verifying the model.

These prototype measurements were taken during ebb flows, at a tidal range of 14 feet and a river flow of 7,300 cfs, the HH combination used in the model tests and listed in Table I. The maximum average spatial velocity reported by Longfield was 2.3 fps occurring about one-third of the way through a tidal cycle beginning at high water slack. This average velocity was obtained by dividing the total downstream discharge (found from isovel plots of many point readings) by the cross-sectional area. The water surface elevation at the time of the maximum ebb velocity was 2.0 feet above MLLW, and the mean water level during the half cycle between high and low tides was 4.0 feet above MLLW.

The average velocity over the cross-sectional water area at the west Spokane Street Bridge could not be measured in the model and compared with Longfield's data, for two reasons. First, model measurements using the drogues described in Chapter IV were confined to the center of the waterway in order to obtain non-grounding operation of deep-penetration drogues. A midget current meter was not available for velocity measurements and it is likely that the small scale of the model would have precluded its use at the Spokane Street Bridge anyway. Second, it is not clear what the alignment was of the waterway cross-sectional area used in Longfield's report, whether parallel to the bridge or perpendicular to the channel centerline.

The verification procedure used was to compare depth-integrated average velocities on the centerline at the opening between the bridge piers. The maximum vertical average velocity of 2.7 fps on the centerline as determined from the isovel plot given by Longfield (1971) was duplicated in the model as closely as could be determined by experimental procedures in the model. The limitations of the drogues and the drogue position plotting procedure could not guarantee an exact vertical average velocity match between model and prototype. Indicated differences in water levels could also induce discrepancies. Even so, the model-prototype comparison obtained was considered adequate to allow results of further model tests to be valid.

The large, skewed piers of the west Spokane Street Bridge constitute a major control on flows through the West Waterway, and were an essential component of the model.

Maximum Velocities in the Harbor Island Reach

The effects of the proposed modifications of the East Channel on maximum ebb velocities in the Harbor Island Reach of the West Waterway were examined for the 14-foot tide range, 7,300 cfs river flow combination only.

The data from the drogue plots were used to construct the two curves described in Chapter IV. Figure 12 shows a sample number of the first curves (velocities at certain stations along the reach during prototype time intervals on the ebb portion of the tide curve) for the case of full closure of the East Channel. The repeatability of the curves was quite good, i.e. the velocities vary in much the sane manner along the reach during different time intervals on the ebb tide. The variation in the shapes of the curves came from inherent errors in the visual tracking of the drogues and the slightly different pathlines followed by the drogues during each individual run; some of this variation could be attributed to the inability to always insert the drogue at exactly the same point with respect to channel centerline for each run. The characteristic pathline of drogues released on centerline of the Harbor Island Reach near the south end of Harbor Island is shown in Fig. 13. The effects of both the piers of the west Spokane Street Bridge and of the channel bottom topography are evident in the pathline plotted. In plan view the flow enters the main West Waterway much as a two-dimensional jet. Not shown on Fig. 13, but evident from visual observations of dye patterns in the model are the two separation eddies induced, one on either side of the stream, as it enters the main West Waterway.

The results of all data represented by the curves of Fig. 12 were replotted to give the variation of velocity (depth averaged) with time on the pathline shown on Fig. 13 at the southwest corner of Harbor Island (identified in this report also by the arbitrary stationing x = - 600 ft.). The replotted data are shown on Fig. 14, which shows the effect on maximum velocity at this station as the East Channel configuration is varied. Neither of the two curves for the closure configurations show the significant increase in maximum velocity which might be expected intuitively as associated with the release of greater amounts of Duwamish Waterway and Duwamish River channel storage through the West Waterway as the East Waterway is closed further. Tests for the two closure conditions did show slight increases in maximum velocity as the East Channel was progressively closed, and the duration of higher velocities likewise increased. The maximum average velocities listed in Table III are taken from Fig. 14; the implied precision only emphasizes the relatively minor changes.

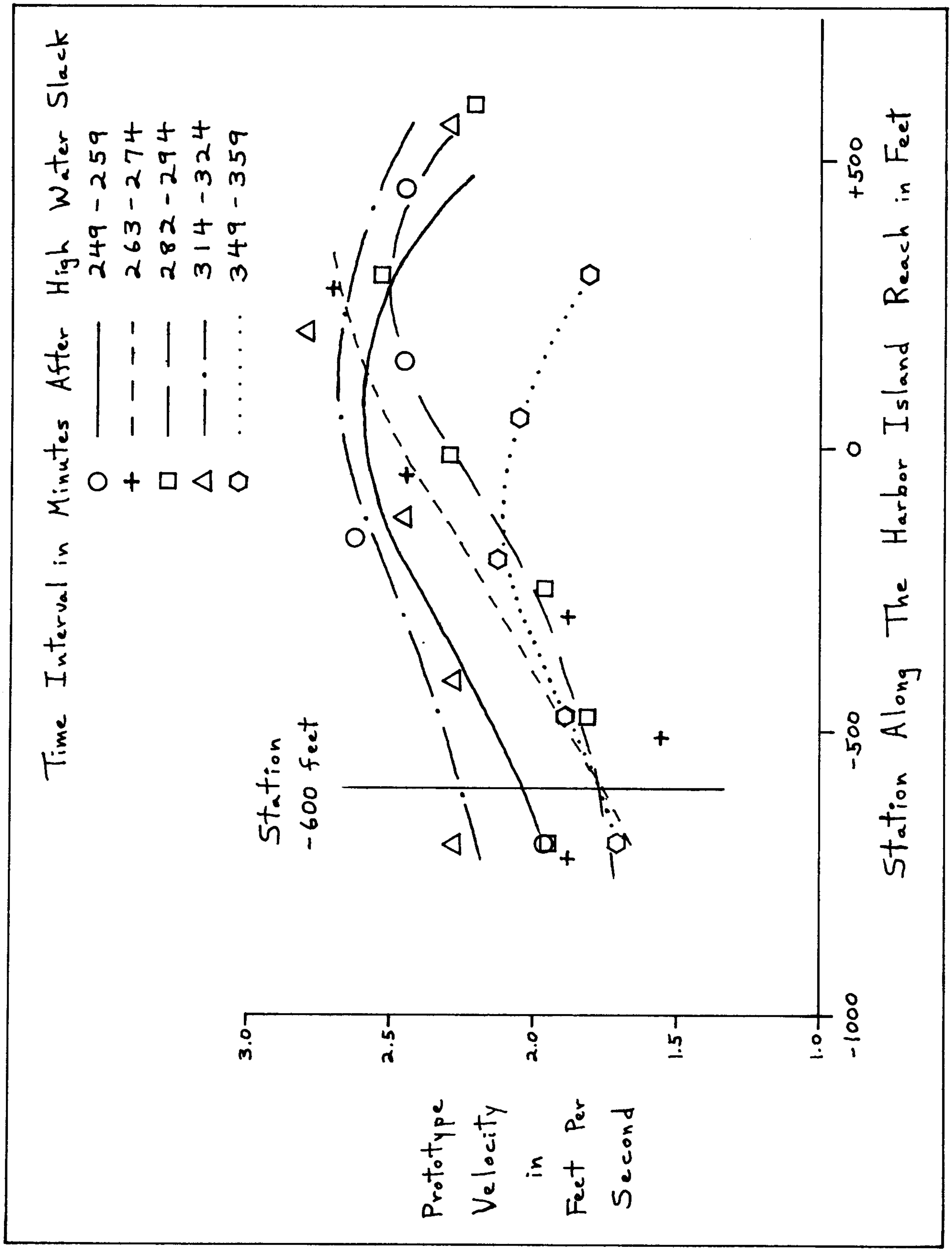

Figure 12- Velocities at Stations Along the Harbor Island Reach During Different Time Intervals on the Ebb Portion of the Tidal Curve--Full Closure

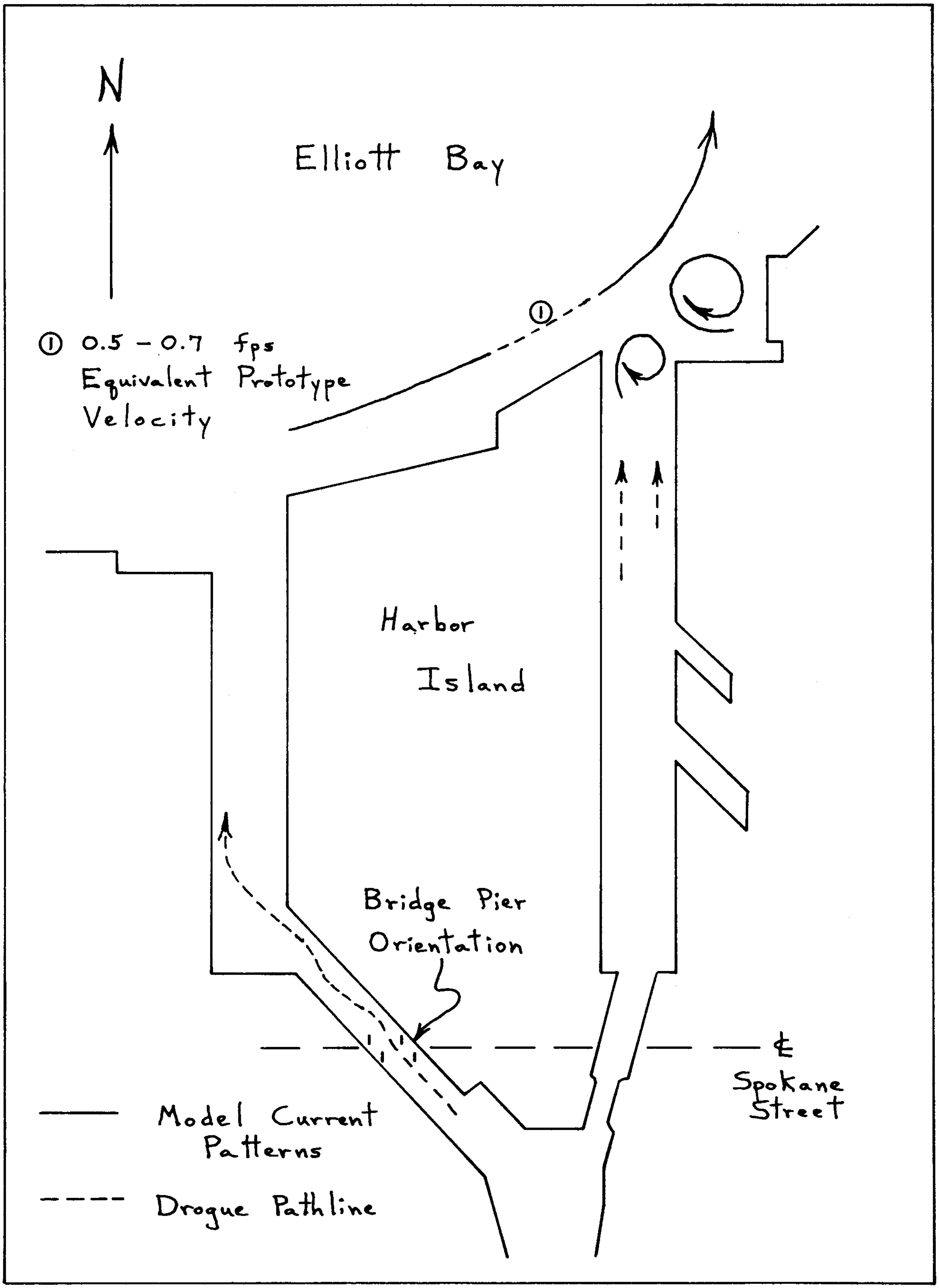

Figure 13 - Drogue Pathlines and Current Patterns on the Ebb Tide

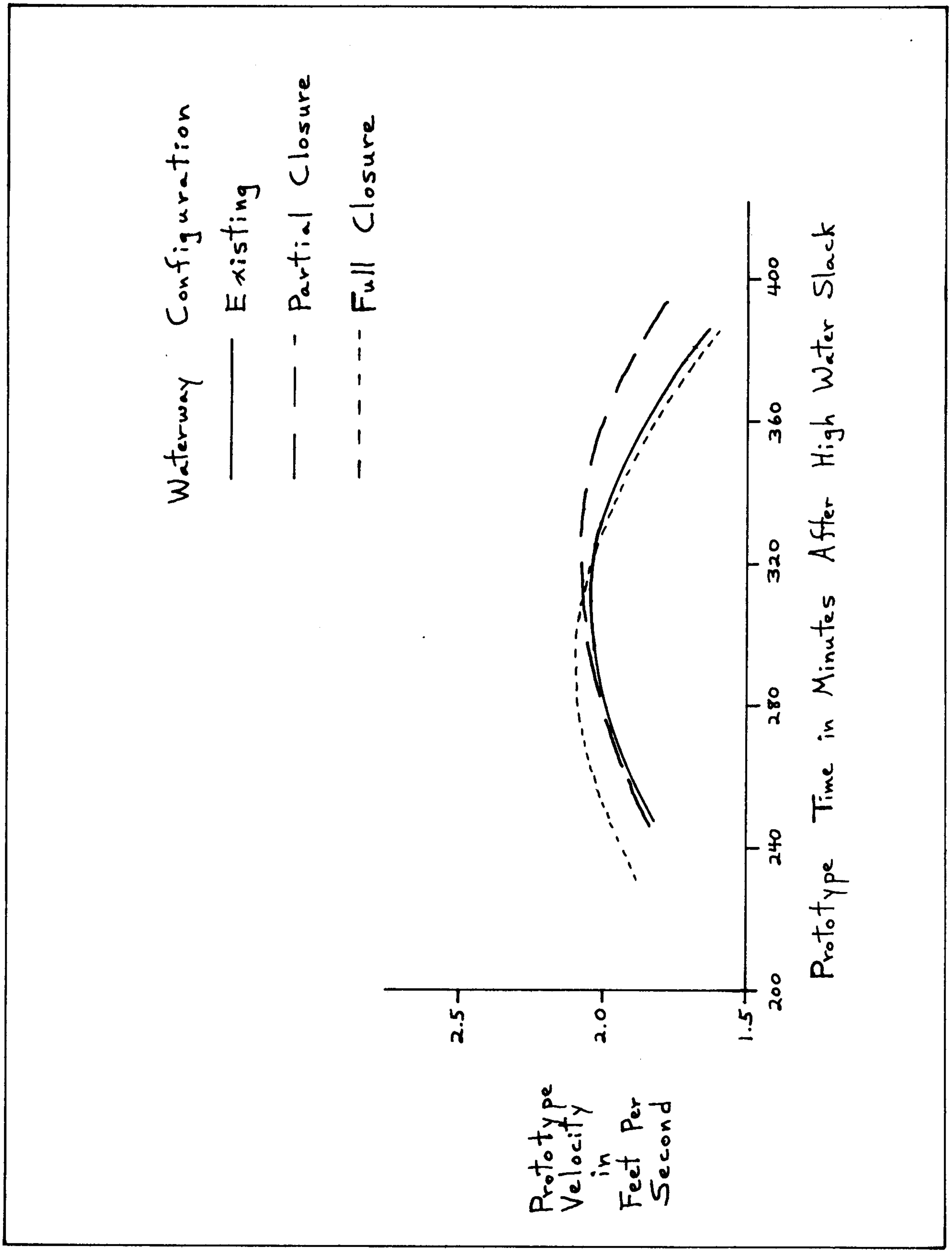

Figure 14 - Comparison of Velocity Variations with Time at the Southwest Corner of Harbor Island at the Three East Waterway Configurations

Table III

Maximum Average Velocities, Harbor Island Reach at West Waterway, for H = 14 ft, Q = 7,300 cfs

Existing Configuration	2.05 fps
Partial Closure of East Channel	2.08 fps
Full Closure of East Channel	2.10 fps

Flushing of the East Waterway

The experimental method for measuring exchange coefficients described in Chapter V had been used previously in model studies making use of the same model basin and has been reported by Lewis (1972) and by Richey and Nece (1972). In both studies the embayments investigated (actually artificially enclosed smallboat harbors) had restricted single openings leading to the ambient external tidal body of water, the physical amplitudes of the tidal ranges in the model were larger than in the present study, and model currents were greater. Departures from these previous conditions influenced the interpretation of the dye exchange results of the present model study.

The exchange coefficients E found under regular model operating conditions for each of the twelve East Channel configuration-tide and river flow combinations are listed in Table IV as the 'gross'exchange coefficients.

In a study of the Des Moines Marina by Lewis (1972), it was found that over most of the tidal range covered there was quite good agreement between measured exchange ratios and those calculated using the conventional tidal prism method; the greatest difference was 18 percent of the measured value, at the lowest tide range, and the root mean square difference was under 6 percent.

A comparable comparison was made for the present study, using the full closure configuration. Dimensions of the simplified East Waterway corss-section shown in Fig. 15 were used in the calculations. The assumptions involved in the calculations were that all water initially in the waterway mixes over the entire waterway volume with any incoming water at high water slack, that the tidal prism volume (volume between high and low water slack levels) of mixture leaving the waterway is completely mixed, and that none of the water leaving the waterway on an ebb tide returns; these represent optimum exchange conditions. Tidal prism exchange ratios of 0.25, 0.15, and 0.06 were calculated for the three tide ranges used, in descending order. These values are listed in Table IV. For the full closure condition, where river flow should have no significance because it was now all diverted through the West Waterway, the gross exchange coefficients were larger than the values based on tidal prism theory; the smallest percentage difference, based on the measured gross values, was 22 percent.

Two features of the model were considered to be the main reasons for the dye leaving the East Waterway at a much greater rate than predicted by the tidal prism approach. First, the combination of a large contact area between the waterway and the bay, coupled with lower velocities, increased the possibility of dye transport out of the waterway over the entire tidal cycle by diffusive transport due to the concentration gradient. The second factor was that currents in Elliott Bay in the model, while reproducing the general current pattern indicated on charts of the United States Department of Commerce, Coast and Geodetic Survey (1961), were higher than those existing in the bay. Measurements in the model gave equivalent prototype velocities of 0.5-0.7 fps off the north-east corner of Harbor Island (see Fig. 13).

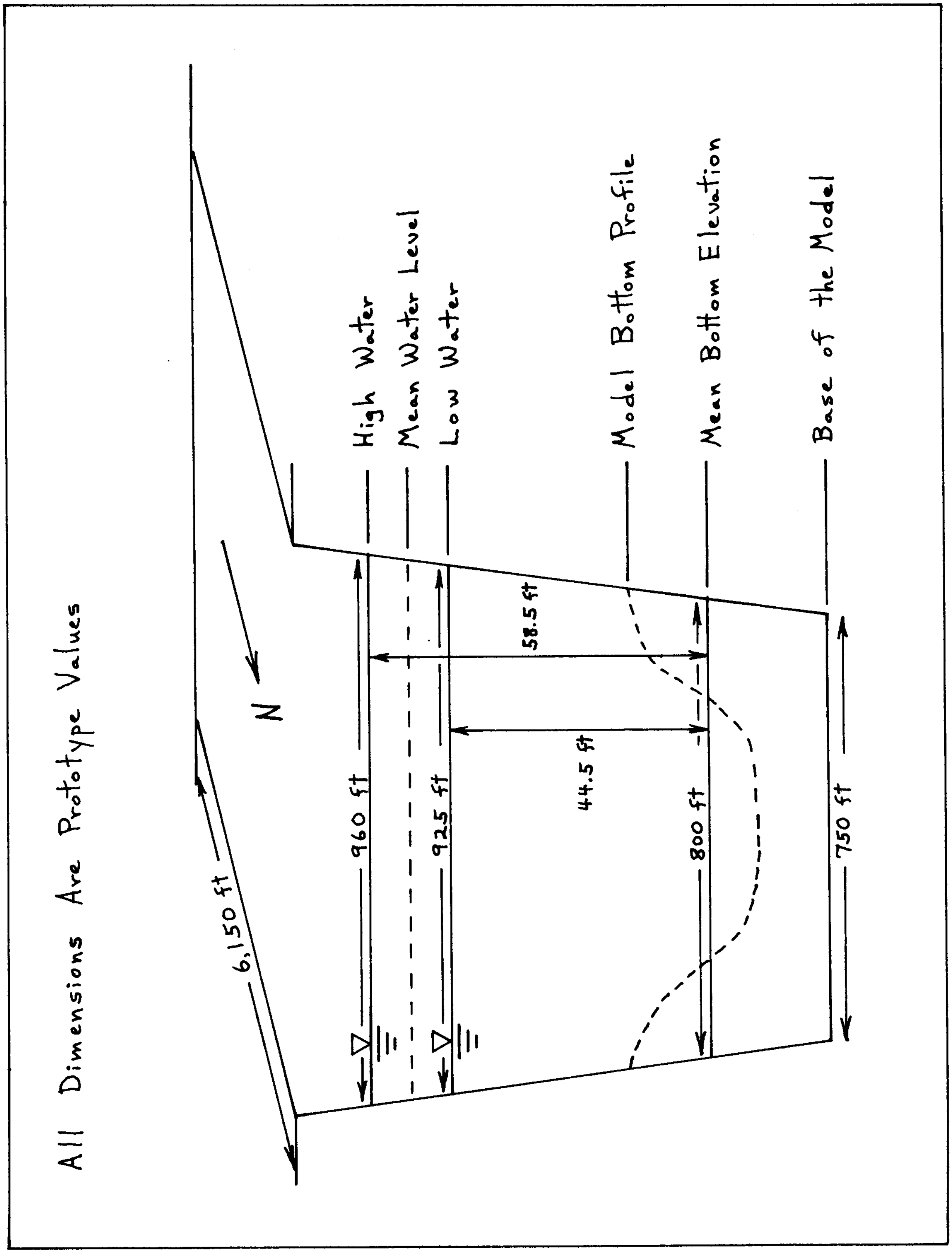

Figure 15 - Simplified East Waterway Cross-Section Used in the Model Study - Full Closure, 14.0 feet Tidal Range, Mean Water Level at 6.6 Feet Above MLLW

These currents were instrumental in forming eddies at the mouth of the East Waterway, as also shown on Fig. 13. The eddies persisted into the flood tide, so that some flushing was taking place which was not accounted for in any conventional tidal flow calculation method. Neither of these two factors could be modified easily during the flushing run, so the exchanges in the model remained high.

A separate approach was used to check the validity of applying the tidal prism concept to the full closure case. A one-dimensional tidal flushing model given by Richey (1971) gave another way of calculating exchange coefficients. For a rectangular cross-section waterway of constant width and horizontal bottom, the following relationship may be obtained:

$$\frac{L - X_o}{L - X} = \frac{Z}{Z_o} \qquad (3)$$

where L = length of the East Waterway

X_o = position of water particle at $z = Z_o$, $t = 0$ (high water slack)

X = position of water particle at $z = Z$, $t = T/2$

Z_o = waterway depth at high water slack

Z = waterway depth at low water slack

T = tidal period

Figure 16 is a definition sketch for Eq. (3).

Letting $X = 0$ at $z = Z$, solving for X_o in Eq. 3 gives the farthest upstream location from which a particle starting at rest at high water slack will reach the mouth of the waterway on the ebb tide. Converting the trapezoidal

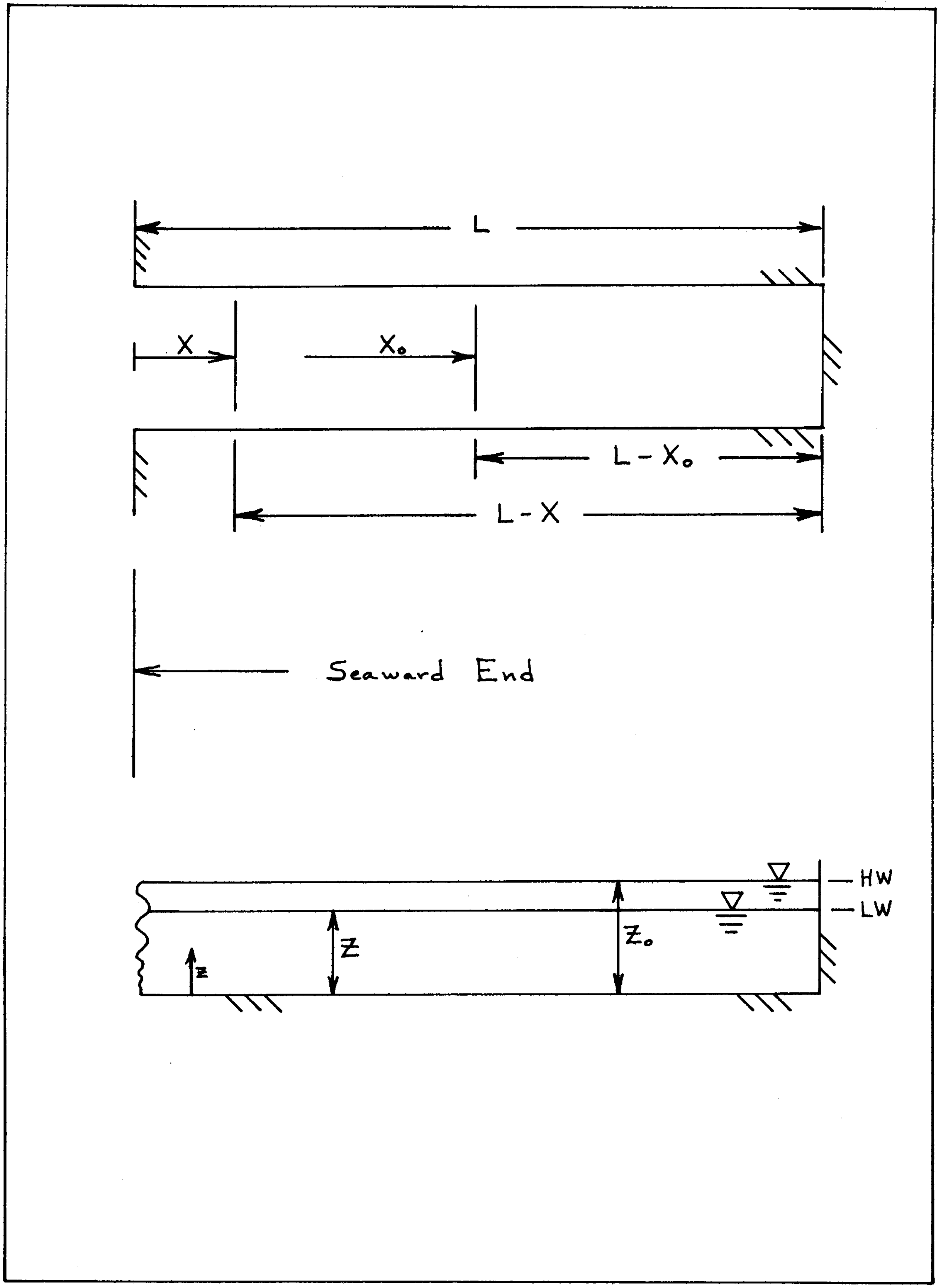

Figure 16- Definition Sketch, Flushing Model

cross-section of the waterway shown in Fig. 15 to an equivalent MWL rectangular cross-section of 942.5 by 47.6 feet, the 14-foot tidal range gives $X_o = 1,580$ feet. This excursion distance implies that all water in the waterway from $X = 0$ to $X = 1,580$ feet will leave on the ebb tide. Dividing by the total waterway length of 6,150 feet gives an exchange coefficient of 0.26. This number checks the tidal prism value of 0.25, the numerical difference being involved with approximations used to obtain the simplified geometries. The two methods should check, as they both are based on the continuity equation.

Drogues released at high water slack at a point 1,580 feet south of the open mouth of the fully closed East Waterway tended to exit from the waterway on the ebb portion of the 14-foot tidal range. These drogue motions were observed to be influenced by the eddies present at the mouth of the waterway; the longitudinal velocity profile in the waterway was skewed, with drogues on the west side of the channel moving faster than those on the right. Equation (3) was tested further by releasing drogues from station $X = 1,500$ feet at high water slack and the mean 7.6-foot tidal range. The predicted excursion distance was 800 feet; measured excursion distances of the drogues were 1,240 feet for a drogue started near the west bank, 710 feet for one started at the west one-third point, and 510 and 770 feet for two drogues inserted close to the centerline. The asymmetry of the velocity profiles was a consequence of the eddies near the waterway mouth. The average excursion was close enough to the distance calculated from the one-dimensional equation that the tidal prism value of the exchange coefficient was considered valid for the full closure configuration of the East Waterway.

The different between the E values from the dye tests in the model and those calculated from the tidal prism theory for the full closure condition for the three tidal ranges were then assumed to be due to the features of the model discussed above. Accordingly, all of the gross exchange coefficients for each tidal range were reduced by the amount required to make the value of E for the full closure case agree with that predicted by the tidal prism theory. The resulting values are listed as the 'net' exchange coefficients in Table IV, and are plotted on Fig. 17. The gross values of E for the full closure case, MM and ML cases, were 0.22 and 0.21, respectively; in the model the river flow had little effect on the fully closed waterway, as anticipated. The constant correction factor applied to all ML runs was 0.06 instead of the 0.07 used for the MM case in order to make the two cases agree at the calculated E = 0.15 from the tidal prism method.

The resulting net exchange coefficients indicate that the greatest changes in water exchange in the East Waterway occurred for the mean tidal range - mean river flow case, with the spatially averaged exchange coefficient (per cycle) decreasing from 0.27 under existing conditions to 0.15 under full closure, a 44 percent reduction in gross water exchange. For the ML combination, that considered applicable to summer low flows in the Duwamish, the reduction in the per cycle E is only from 0.21 to 0.15; the influence of river flow on the flushing is evident.

The single flushing test of the bridge pier layout shown in Fig. 4, run at the ML combination, yielded a net exchange coefficient of 0.21, the same value as for the existing configuration. The relatively small piers, which are incorporated into a cable stayed bridge design considered by the City of Seattle Engineering Department, have no significant effect upon flows through the East Channel. Those piers which are starred in Fig. 4 barely penetrate the water cross-section. It can be concluded that the bridge pier arrangement tested would have no effect upon flushing of the East Waterway.

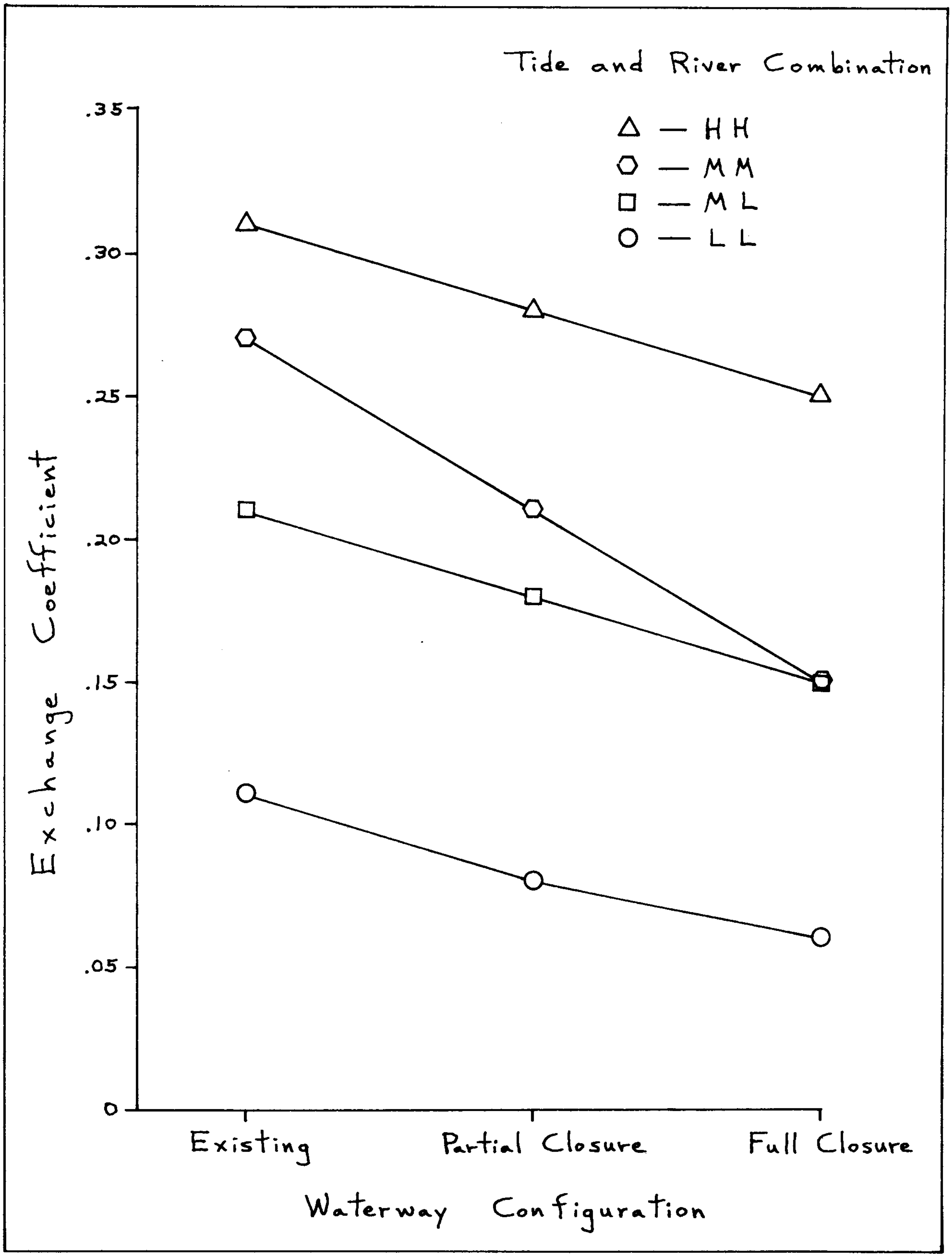

Figure 17 - Comparison of the Exchange Coefficients for the East Waterway at the Four Tide and River Combinations and the Three East Waterway Configurations.

Table IV

Exchange Coefficients - East Waterway

	Test Combination	Gross Exchange Coefficient	Correction	Net Exchange Coefficient
Existing Conditions				
	HH	0.38	0.07	0.31
	MM	0.34	0.07	0.27
	ML	0.27	0.06	0.21
	LL	0.26	0.15	0.11
Partial Closure				
	HH	0.35	0.07	0.28
	MM	0.28	0.07	0.21
	ML	0.24	0.06	0.18
	LL	0.23	0.15	0.08
Full Closure				
	HH	0.32	0.07	0.25*
	MM	0.22	0.07	0.15*
	ML	0.21	0.06	0.15*
	LL	0.21	0.15	0.06*

*From Tidal Prism Calculations

VI. CONCLUSIONS

Interpretation of Model Results

The validity of any model, mathematical or physical, should be checked before its results are applied to the job at hand. This report has detailed areas of question about the present model; it therefore is appropriate to discuss these questions to establish the validity of the small, single-fluid model.

The data of Longfield (1971) did not show any stratification effects on the ebb flow maximum currents in the Harbor Island Reach. For the full closure, the most severe condition from a water quality standpoint in the East Waterway, there is no fresh water inflow to the waterway to cause stratification and the waterway would act simply as a closed arm of Elliott Bay. As a result of their study of the Duwamish River estuary, Santos and Stoner (1972) indicated that stratification becomes less distinct at lower river inflows. Therefore, for the particular purposes of the model as applied to the more critical flow conditions, use of the single-fluid model was justified.

Reasons for the apparently high gross exchange coefficients given by the direct dye concentration measurements in the model have been partially explained in Chapter V. Toward the end of the testing program it was decided that the abnormally high currents in Elliott Bay which seemed to be a large part of the problem might have been eliminated by eliminating the lower sections of the aprons simulating the bottom contours of Elliott Bay; this would have allowed water to move more freely in the entire basin without forcing most of the water supplied to the basin from the distribution manifold to circulate in the relatively small part of the basin, between the outer (northern) limits of the model and the tank baffles. Lack of time prevented this change being made and all previous data re-run. There is also a question about how much effect the actual dye concentration used had on the diffusive transport out of the waterway. The high concentrations used in the study were selected partly for visibility purposes; reduced concentrations may have given other numbers.

However, the drogue excursion checks on the tidal prism-continuity models, as discussed in Chapter V, produced a fairly good check on the calculated results. It is concluded that the correction methods used to adjust the gross exchange coefficients to the net exchange coefficients are valid, and that the quoted final results are quantitatively adequate for evaluating the investigated hydraulic consequences of the various degrees of closure in the East Channel.

Summary of Results

1. The closure schemes investigated have no appreciable effect on the magnitudes of the ebb flow currents in the Harbor Island Reach.

2. For the high tidal range and high river flow combination, complete closure of the East Channel will reduce the per-cycle exchange of water in the East Waterway by 19 percent, compared to the exchange under existing conditions; the comparable reductions are 44, 29, and 45 percent, respectively, for the mean tidal range - mean river flow, mean tidal range - low river flow, and low tidal range - low river flow combinations, respectively. The significance of these changes can be evaluated only after they are incorporated and tested the appropriate mathematical models for water quality parameters.

3. The pier arrangement for a proposed stayed cable bridge has no appreciable effect on flushing characteristics of the East Waterway.

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