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# CHL Precision Flow Table—Description and Applications

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**PURPOSE:** The Coastal and Hydraulics Engineering Technical Note (CHETN) described herein provides information about the new precision flow table experiment facility located at the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (CHL). The precision flow table can examine complex steady flow problems rapidly and at low cost. This capability is useful for understanding complicated flow problems and deciding on whether to pursue more elaborate modeling technologies. A description of the flow table capabilities is given along with an example application related to flow at a tidal estuary.

**FLOW TABLE OVERVIEW:** Coastal engineering has a rich tradition of using laboratory facilities to reproduce at small scale, flow phenomena present at coastal projects. Common physical modeling facilities include wave flumes, wave basins, and current flumes. These laboratory tools are used to study complex hydrodynamic processes, to optimize engineering designs, and to provide validation data for developing numerical modeling approaches.

Recently, CHL constructed a new precision flow table to examine flow problems related to tidal currents interacting with inlet jetty structures. The table flow system maintains a constant flow discharge across a horizontal portion of the table through a recirculating system regulated by valves. Water depth is controlled by a downstream adjustable weir. Small-scale models depicting either idealized flow boundaries or portions of actual projects are placed on the glass horizontal test section of the flow table. Flow patterns created by the scale model solid boundaries, such as regions of flow separation and turbulence generation, are quantified using a laser Doppler velocimeter (LDV) located beneath the horizontal section of the table. The laser beams pass through the glass bottom and measure two horizontal components of velocity at the vertical elevation where the laser beams intersect. Complex flow patterns can also be visualized using traditional techniques of dye injection, surface tracers, and bottom tracers.

**APPLICATIONS:** The precision flow table is particularly well suited for quick, inexpensive studies related to quasi-steady flow interacting with solid boundaries. For example, idealized inlet geometries can be easily constructed on the flow table using rectangular blocks or specially molded pieces resembling rubble-mound structures. Consequences of structure modification, extension, or realignment are easily observed and quantified without the time and expense associated with larger-scale physical models or complex numerical hydrodynamic simulations. Tide reversal is achieved by turning the model inlet on the table so the flow comes from the opposite direction.

Because of the small scale, numerous project options and configurations can be examined in only one or two days with minimal preparation. This capability is ideal for brainstorming new concepts related to channel optimization and maintenance. Those alternatives deemed worthwhile can then be studied in more detail using sophisticated numerical codes and large-scale physical models. Thus, the flow table can be used to winnow out proposed project alternatives early in the study which will reduce the cost of the more detailed follow-on efforts.

The flow table reproduces complex flow phenomena such as flow separation, flow entrainment, turbulence, three-dimensional (3-D) flow structure, and cross-channel transport. For U.S. Army Corps of Engineers (USACE) projects where these processes are thought to be significant, the flow situation can be clarified by fabricating a scale model of the actual bathymetry and shore boundaries for use on the flow table. Flow patterns are visualized using the aforementioned techniques so that complex flow/boundary processes are better understood. Changes to bathymetry or upstream boundaries are easily simulated, and the impact is immediately observed. This type of flow table study helps assure that more extensive study tools, and corresponding proposed solutions, address the dominant causative hydrodynamic factors. For example, if strong 3-D circulation is evident in the flow table model, it may be necessary to employ a 3-D hydrodynamic numerical model rather than a two-dimensional (2-D), depth-averaged numerical model to describe adequately the consequences of engineering modifications. Also, the flow table can efficiently screen potential project alternatives so that follow-on detailed studies are more focused and cost-effective.

In addition to studies supporting existing or planned USACE projects, the flow table can also be used to study fundamental flow processes such as 3-D flow, boundary layers, and the velocity structure in turbulent jets. Because many complex flow phenomena such as separation and turbulence are reliably reproduced in small-scale physical models, the flow table can be used as a validation tool in conjunction with development of advanced hydrodynamic numerical models that incorporate these features.

**FLOW TABLE DETAILS:** The flow table, shown schematically in Figure 1, is approximately the size of a billiards table. Flow of water from the constant head tank (**HT**) is controlled by a valve that assures a steady flow rate feeding the upstream basin (**IN**). Water flows across the horizontal (2.44 m $\times$ 1.22 m) glass bottom of the flow table and spills over the adjustable-height weir into the catchment tank (**OUT**) which in turn overflows into the reservoir (**RES**). The reservoir is detached from the flow table to isolate vibrations of the pump as water is recirculated to the head tank. The discharge rate onto the flow table is controlled by an adjustable valve (**A1**) and flow meter. Under operating conditions the flow table holds approximately 0.91 $m^3$ (240 gal) of water plus an additional 0.08 $m^3$ (21 gal) for every inch of water depth over the glass bottom.

Flow velocities on the water table are measured with a two-component laser Doppler fiber-optic probe mounted on a horizontal traversing system beneath the 19-mm-thick glass bottom. Laser beams emanating from the probe pass through the bottom glass and intersect at a known position (adjustable) in the water column. Velocities are determined at the beam crossing point; hence, the measurement system is totally nonintrusive so the flow is in no way disturbed by the measuring system. Traversing of the LDV probe is computer controlled in two horizontal directions allowing automatic recording of velocity at precise, predetermined locations throughout the testing area. Usually, velocity data are collected on a uniformly-spaced grid with the probe collecting a time series of instantaneous velocities at each grid point before moving to the next location. The velocity time series in the two orthogonal horizontal directions at each point are averaged to provide two components of the velocity vector. Sampling rate and duration are adjustable, but typically data are collected at 100 Hz for a duration of 10 sec at each point. Because the flow is quasi-steady, the final result is a map of velocity vectors detailing the flow throughout the measurement region as illustrated in Figure 2.

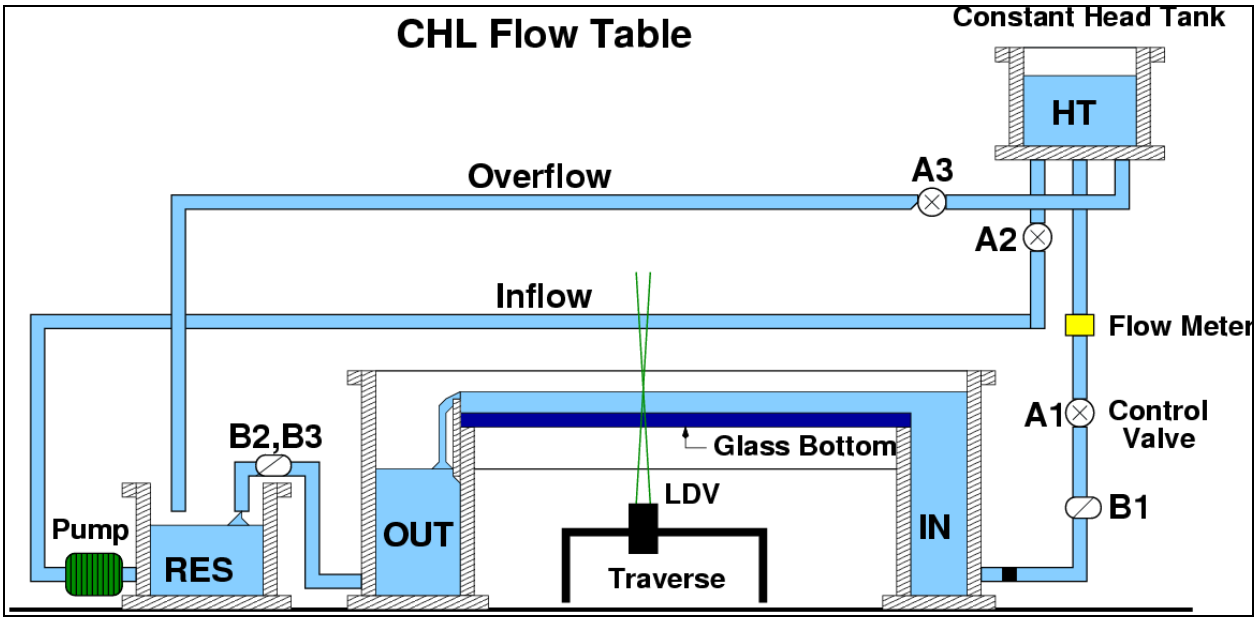


Figure 1. Schematic side-view showing flow table components

Velocity measurements using the traversing LDV system require a transparent horizontal bottom so that the four individual laser beams will have equal refraction and converge at a point. Consequently, velocity measurements cannot be made if project bathymetry is carved into Plexiglass and placed over the horizontal glass bottom because the laser beams would not converge to a point. However, a compromise is possible if the bathymetry is idealized as a series of stepped horizontal surfaces fabricated of Plexiglass so that it resembles a submerged terrace. Flow quantification for models incorporating complex 3-D bathymetry must be done using surface-piercing instruments such as LDV probes, micro-impellers, or time-lapse photography of surface tracers.

**SCALING CONSIDERATIONS:** Flow table models are much smaller than physical models of coastal projects typically constructed at CHL. The major consequence of the small size is that most models of actual projects will be geometrically distorted. This means the horizontal length scale will be larger than the vertical length scale. In other words, one inch in the horizontal direction in the model represents a larger distance in the prototype than one inch in the vertical direction represents. Model distortion allows larger areas to be included in the model while maintaining sufficient water depths to avoid surface tension effects. Geometric distortion is justified and accepted for flow models without waves so long as vertical velocities and accelerations are small compared to horizontal flow velocities. Scaling relationships for geometrically distorted physical models are well established and widely accepted (e.g., Hughes 1993).

Significant vertical fluid motions might exist in turbulence regions associated with flow separation at boundaries or solid objects placed in the flow, and this may be the one situation where geometric distortion could cause similitude problems. In a distorted model, there will be scale effects associated with four of the nine turbulence terms represented in the Navier-Stokes equations of fluid motion. Potential scaling impacts increase as the turbulent velocities in the vertical direction approach the same order of magnitude as the horizontal turbulent fluctuations. However, this potential scaling limitation is partially overshadowed by the five turbulence terms that are in similitude.

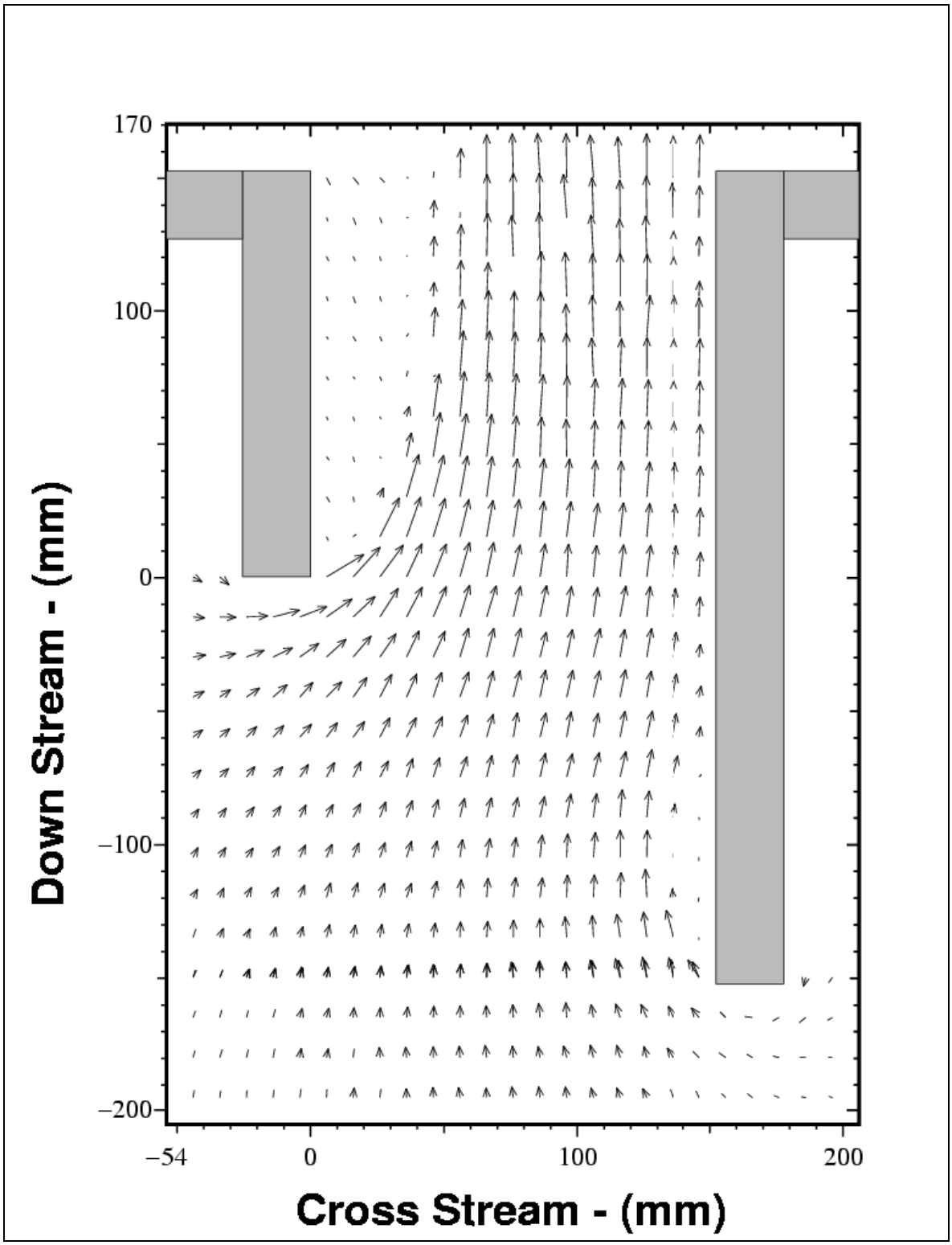


Figure 2. Velocity field at unequal length jetties

One of the first studies conducted on the CHL flow table (Hughes and Pizzo, in preparation) examined the potential for turbulence scale effects in distorted models. Various solid boundary configurations were used to create turbulent flows which were measured using the laser Doppler system. These were taken to be the "prototype cases." Then, distorted models of these same configurations were tested, and the measured velocities of the distorted models were scaled and compared to the prototype results. Turbulence generated by flow past vertical edges was in similitude in distorted models because the turbulence was mainly in the horizontal plane with small vertical velocity fluctuations. Turbulence generated at sloping edges exhibited a scale effect closer to the bottom, but near the surface the flow was in near similitude. There were no scale effects within the main region of nonturbulent flow. Finally, turbulence created by flow past a horizontal step was also shown to be in similitude because the turbulence was mostly manifested in the vertical plane with only small horizontal turbulent fluctuations.

Another potential cause for dissimilar flow patterns is nonturbulent flow around a bend which is known to generate secondary or helical flows. Hughes and Pizzo (in preparation) performed a theoretical analysis of potential scale effects and concluded that scale effects would exist in a distorted model, but this may not be critical provided the model has adequate bottom roughness to help balance the effect of the cross-channel centrifugal acceleration. It was noted that most numerical modeling neglect the convective accelerations that will not be in similitude which implies these terms have minor influence. No experimental data were given to support this hypothesis.

In summary, there will be scale effects present in geometrically distorted models where large-scale turbulence features such as gyres are generated by solid boundaries. The magnitude of the scale effect is difficult to ascertain, but differences between model and prototype decrease as the magnitude of the vertical turbulent fluctuations decreases. Because distorted models have steeper slopes that decrease the magnitude of the vertical turbulence components generated by the slope, it should be expected that the prototype might experience stronger vertical turbulence than demonstrated in the model. Once again, whether or not these scale effects degrade the model results will depend on the goals of the modeling and the relevance of the turbulent flow processes to the specific regions of interest within the study area.

**PROJECT APPLICATION EXAMPLE:** U.S. Army Engineer District, Alaska, sponsored flow table studies to examine the hydrodynamic flow regime in upper Cook Inlet in the vicinity of the Port of Anchorage. Shoaling at Anchorage Harbor during the summer months has required annual dredging that averages between 200,000 and 400,000 $yd^3$ per year with occasional larger deposition quantities between 800,000 and 1,000,000 $yd^3$. The flow table models helped to clarify the flow regime, and flow visualization techniques indicated that shoaling was likely caused by ebb tide flow separation occurring at a headland (Cairn Point) located just upstream of the port. Figure 3 illustrates the approximate line of flow separation and the reduced flow region in the lee of Cairn Point adjacent to the port. This particular finding had not been hypothesized prior to the flow table tests. Details of the study are in Hughes and Pizzo (in preparation).

**Idealized Flow Table Models.** Two types of flow table models were designed and constructed for this study: (a) Idealized models at two different scales with bathymetry represented as two or three horizontal terraces, and (b) a 3-D model that reproduced actual bathymetry. Figure 4 shows

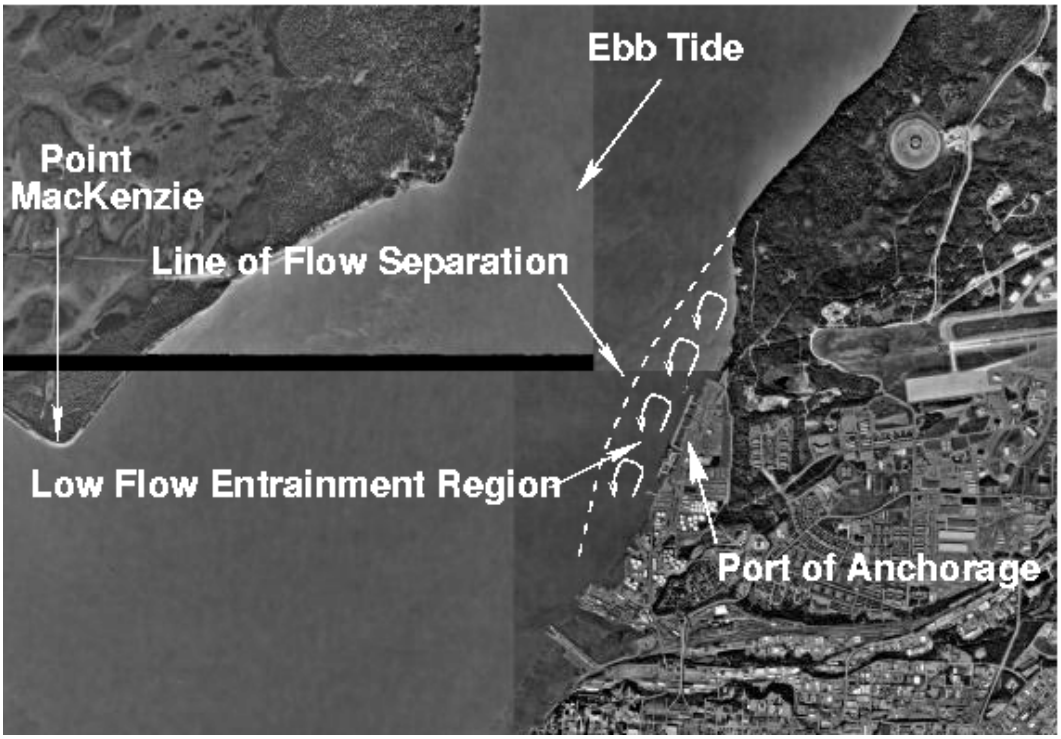


Figure 3. Flow separation off Cairn Point during ebb flow (Cook Inlet, AK)

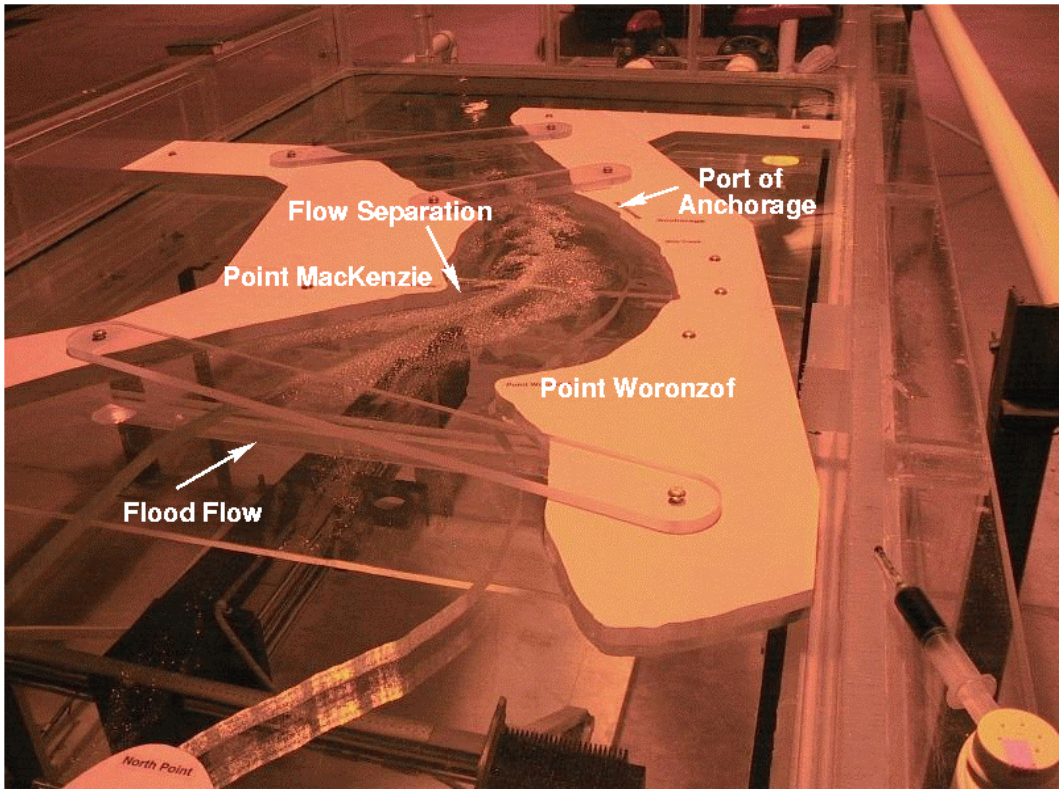


Figure 4. Idealized model of a portion of Cook Inlet, AK, during flood flow

an idealized model of upper Cook Inlet on the flow table. The seaward boundary of the model (bottom of photograph) reproduced about 19.3 km (12 statute miles) across the width of the flow table, and the shoreward end extended about 4.8 km (3 miles) upstream of the Port of Anchorage. Model scales are given in Table 1.

**Table 1**
**Scale Ratios for Idealized Cook Inlet Model**

| Scale | Scale Value | Model Equivalence |
|---|---|---|
| Horizontal scale | $N_X = 15{,}625$ | 1,300 ft ≈ 1 in |
| Vertical scale | $N_Z = 480$ | 40 ft = 1 in |
| Velocity scale | $N_V = \sqrt{N_Z} = 21.9$ | 2.2 m/s = 10 cm/s |
| Discharge scale | $N_Q = N_X N_Z^{3/2} = 164{,}316{,}767$ | 203,000 $m^3$/s = 1.24 liter/s |

Depths in the model were idealized by two horizontal surfaces located at elevations corresponding to elevations of 0 ft and -60 ft mllw. Transitions between the two depths were vertical. A second idealized scale model was also constructed of a smaller area centered on the Port of Anchorage. The seaward boundary of this model represented about 6.4 km (4 miles) across the inlet with a horizontal length scale of 1 in. equaling about 940 ft. Depths in this model were idealized by three horizontal surfaces located at elevations of 0 ft, -30 ft and -60 ft mllw. Transitions between the three depths were vertical.

The two idealized models were constructed from clear Plexiglass which allowed the LDV to record velocities through the horizontal surfaces. Shorelines and depth contours were digitized from nautical charts, and total fabrication cost was about $6,000 for both models.

Engineers from the Alaska District traveled to CHL to observe flow patterns in the models. Over a 3-day period, flow patterns were visualized and observed in both idealized models for maximum flood and ebb flow at different water depths. Flow separation and large vortex regions were evident in the lee of the major headlands as illustrated by the surface tracers shown in Figure 4. The surface tracers created patterns that were qualitatively similar to those observed during the spring ice breakup at Cook Inlet, lending further credibility to the idealized small-scale models.

Figure 5 shows the results of a dye injection that revealed a cross-channel flow along the bottom moving from right to left in the photograph. Flow separation at Point MacKenzie (left side of photograph) during flood flow lowers the water surface along the separation boundary, and the resulting momentum imbalance creates a cross-channel flow at the bottom. In Figure 5 the dye shows a large region of nearly still water that corresponds closely to the existing mud flats formed in the lee of Point MacKenzie during flood tide.

The Alaska District engineers also examined alteration of the flow regime that might be caused by modifications to upstream boundaries. A combination of Plexiglass blocks, small stones, and modeling clay (silly putty) was used to redirect upstream flow, relocate shoals, and investigate possible engineering modifications that might alleviate the Port of Anchorage shoaling problem.

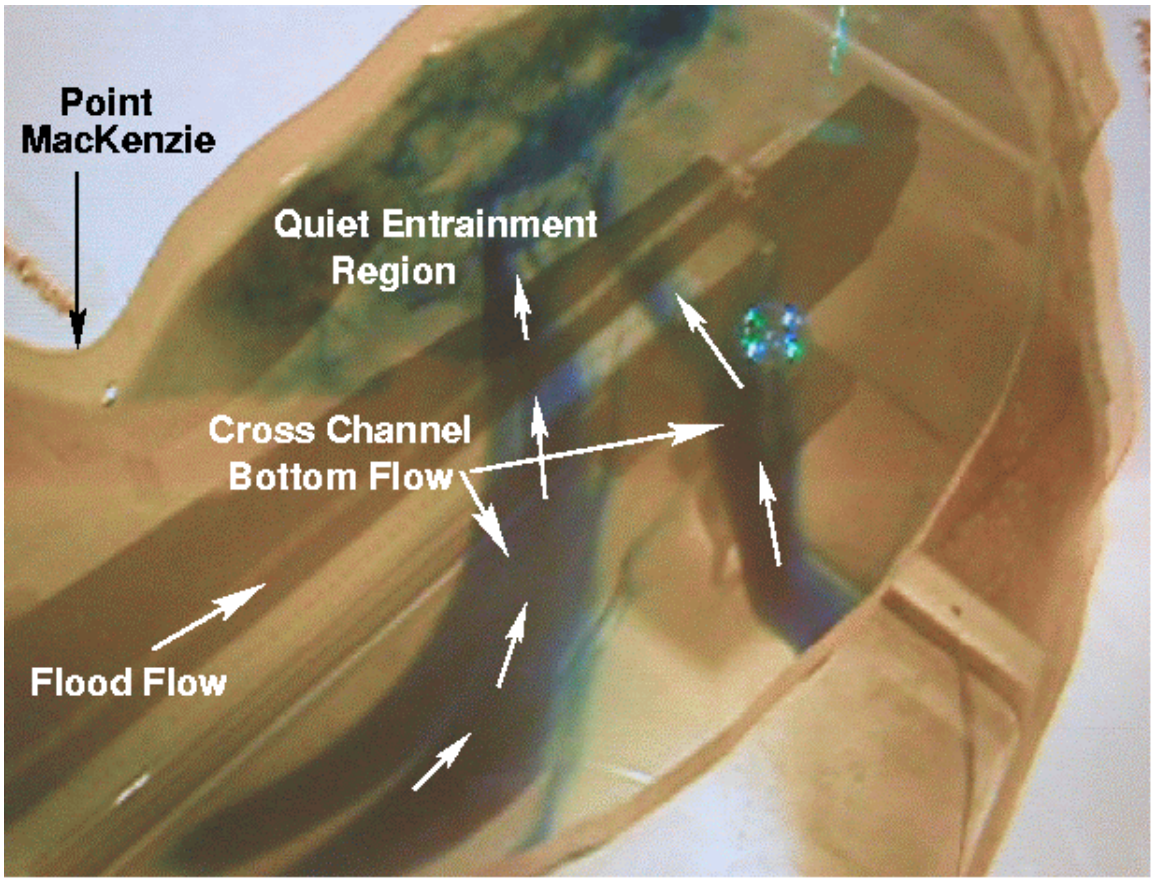


Figure 5. Cross-channel bottom flow at Cook Inlet, AK

Over the 3-day testing period for the idealized models, valuable insight into the complex tidal flow was gathered which led to new understanding of the problems facing the Alaska District. Evidence of strong flow separation and existence of 3-D flow circulation patterns helped the District engineers evaluate various modeling approaches that might be employed in seeking a problem solution. Total cost for the idealized flow table modeling effort was estimated to be less than $10,000 plus travel costs. Benefits derived from the study far outweighed the costs because the overall study then became focused on root causes of the shoaling problem and appropriate engineering methodologies that could be pursued.

**Three-Dimensional Flow Table Model.** The success of the idealized Cook Inlet models prompted the Alaska District engineers to fund an additional flow table model of Cook Inlet featuring actual bathymetry of the study area. The primary purpose of the 3-D model was to confirm that flow patterns and the harbor sedimentation mechanism discovered in the idealized model were not unduly influenced by the terraced bathymetry of the idealized models. A secondary objective was to investigate impacts related to various dredge release sites to optimize dredging operations.

Digital bathymetry covering Cook Inlet over a 49.9-km (31-mile) reach was used to carve the 3-D model using a programmable router. Figure 6 shows a portion of the model carved into 7.8-cm (3-in.-) thick Plexiglass. Relevant scaling factors (prototype-to-model ratios) for the 3-D model are listed on Table 2 along with approximate model equivalences. The model had a horizontal-to-vertical length scale distortion of 15.

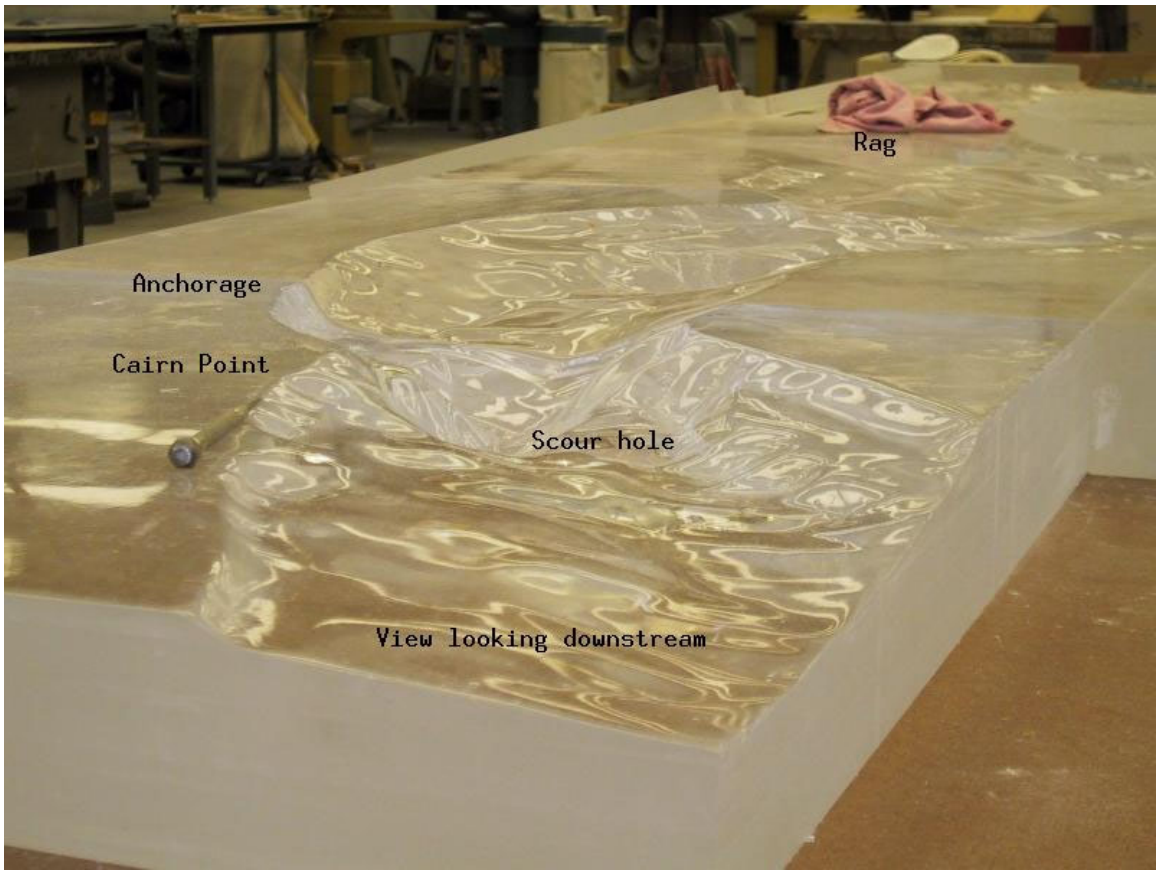


Figure 6. Portion of 3-D Cook Inlet model looking downstream

**Table 2**
**Scale Ratios for Three-Dimensional Cook Inlet Model**

| Scale | Scale Value | Model Equivalence |
|---|---|---|
| Horizontal scale | $N_X$ = 15,000 | 1,250 ft ≈ 1 in |
| Vertical scale | $N_Z$ = 1,000 | 83 ft = 1 in |
| Velocity scale | $N_V = \sqrt{N_Z}$ = 31.6 | 1.6 m/s = 5 cm/s |
| Discharge scale | $N_Q = N_X N_Z^{3/2}$ = 474,341,650 | 203,000 $m^3$/s = 0.43 liter/s |

The model was divided into six sections over the 49.9-km (31-mile) reach, but only four sections (about 32.2 km (20 miles)) could be placed on the flow table at a time. By removing sections on one end and adding sections on the opposite end, different reaches of Cook Inlet could be tested with adequate upstream boundaries represented in the model. This technique effectively extended the modeled region with little additional cost.

Engineers from the Alaska District spent 3 days conducting tests with the new flow table model. All of the large-scale flow structures observed in the idealized models during flood and ebb tide were seen in the 3-D model. This included flow separation at the major headlands, large slow-moving gyres in the lee of the headlands, and ebb-flow reduction at the Port of Anchorage. The same cross-channel transport occurred in the 3-D model at approximately the same location as observed in the idealized model (see Figure 5), but in the 3-D model the cross-channel flow was somewhat weaker. The weaker current may be attributed to differences between actual and idealized bathymetry. But overall it was shown that the less expensive idealized models reproduced dominant flow patterns reasonably well.

Simulation of maximum ebb flow over the actual bathymetry of the 3-D model generated the same reduced flow phenomenon at the Port of Anchorage as was observed in the idealized models. Figure 7 shows ebb currents moving surface tracers (baby powder) past Cairn Point. Most of the tracer had already moved downstream with the exception of the tracer particles caught in the gyre formed in the lee of Cairn Point. Within the gyre the tracer particles slowly circulated in a counterclockwise direction. Fine sediment entrained in the water would have ample opportunity to deposit on the bottom while trapped in the gyre.

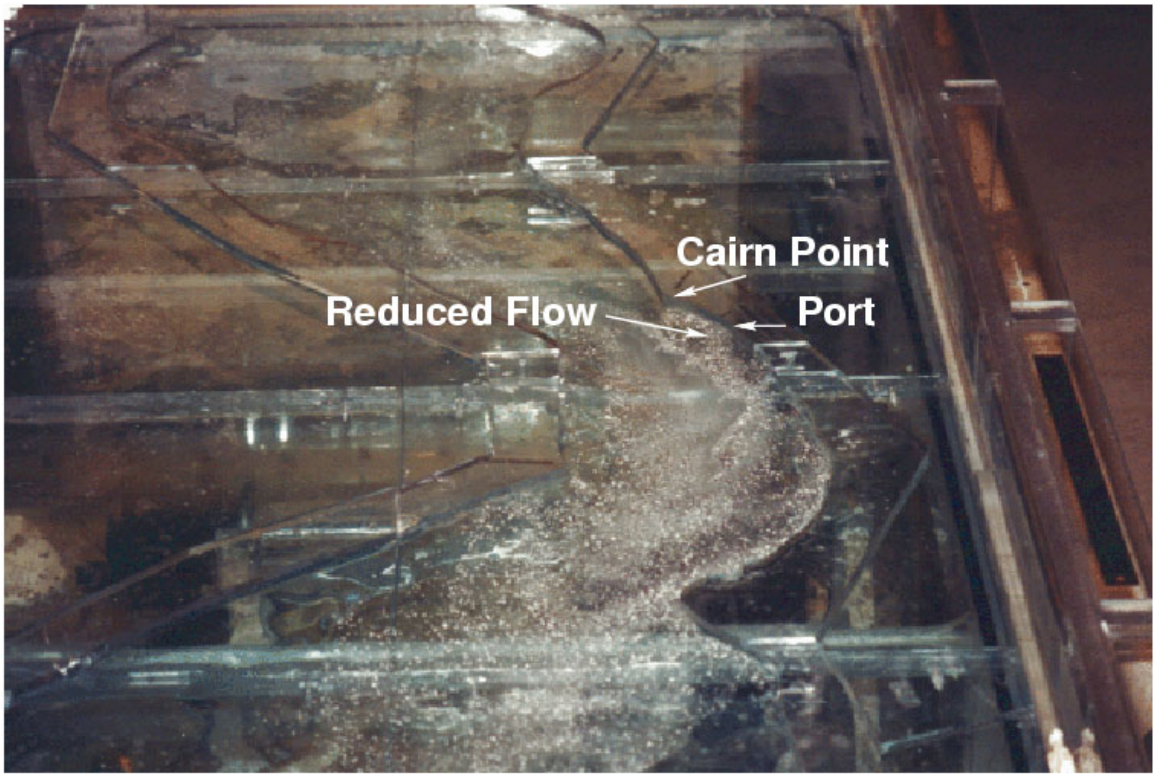


Figure 7. Surface flow tracer showing reduced flow at Port of Anchorage during ebb tide

Alaska District engineers used injected dye to investigate how dredged sediment might move when deposited from barges at different locations during both ebb and flood flows. Approximate locations of established dump sites were scaled on the model, and dye was slowly injected at various depths in the water column. Depending on the flow direction and the injection point, it was not unusual to observe dye migrating back into the vicinity of the port. Movement of the dye injection location, or

dumping during the opposite tide flow often alleviated this problem. These simple experiments revealed more efficient dredging and disposal practices that could substantially reduce the amount of deposited dredge material re-entering the port area.

Total cost for designing, fabricating, and testing the 3-D Cook Inlet model was less than $25,000. However, this modest cost stems from the fact that bathymetry in digital form was available from a companion numerical model study.

**SUMMARY:** The new precision flow table developed under the Coastal Inlets Research Program at CHL provides an efficient and cost-effective tool for examining complex flow patterns formed by solid boundaries such as jetties, bulkheads, groins, and rocky headlands. Flow modifications stemming from changes in boundary or upstream configurations are easily evaluated, and this aids project study optimization by quick identification of unsuitable alternatives. In most cases flow table studies do not provide final design and project optimization, which should be accomplished using more sophisticated tools such as large physical models or numerical simulations.

The flow table simulates only current flow situations; impacts due to waves are not included. Types of studies that can be conducted with this facility include the following:

*a.* Visualizing flow patterns in large estuaries, inlets, or where flow separation and 3-D flow structures are thought to occur.

*b.* Obtaining velocity measurements near structures and in turbulent regions associated with flow separation at solid boundaries.

*c.* Quantifying flow conditions in idealized cases for use in validating numerical modeling techniques.

*d.* Quickly examining project impacts due to structure modification, addition, removal, or relocation.

*e.* Observing the extent of flow three-dimensionality in order to determine the correct numerical modeling approach.

As with all coastal engineering tools, there are advantages and disadvantages related to the precision flow table.

**Advantages:**

*a.* Flow conditions can be controlled precisely.

*b.* The laser Doppler velocimeter provides precise, nonintrusive measurements of turbulent velocity.

*c.* The small size of the table allows rapid (and inexpensive) changing of solid boundaries so numerous experiments can be conducted over a short time period.

d. Complex bathymetry can be recreated at scale for minimal costs.

e. Study costs are low.

**Disadvantages:**

a. Velocity measurements are practical only above horizontal surfaces.

b. Currents are steady in time.

c. No simulation of combined waves and currents.

d. Models of actual projects must be geometrically distorted, so some scale effects will exist.

**ADDITIONAL INFORMATION:** This CHETN is a product of the Scour at Inlet Structures Work Unit of the Coastal Inlets Research Program (CIRP) being conducted at the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory. Questions about this technical note or the precision flow table can be addressed to Ms. Jackie Pettway, Jackie.S.Pettway@usace.army.mil For information about CIRP, please contact the CIRP Technical Leader, Dr. Julie Rosati, Julie.D.Rosati@usacea.army.mil Beneficial reviews were provided by Mr. Dennis Markle and Dr. Nick Kraus, CHL; Mr. Kenneth Eisses, Alaska District,; Mr. Gian-Marco Pizzo, University of California, Berkeley; and Mr. John Oliver, retired USACE, North Pacific Division.

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