POAC '99
Espoo, Finland

Proceedings of the 15th
International Conference on
Port and Ocean Engineering
under Arctic Conditions

DESIGN OF CHANNELS IN ICY WATERS

Orson P. Smith
University of Alaska Anchorage,
Anchorage, Alaska, USA

ABSTRACT

An objective approach is proposed to design channels with ice and other winter conditions. A computation is demonstrated which hypothesizes an initial diversion by ice forces of a ship from a normal sweep path, followed by corrective maneuver at an extended turning diameter. The approach is substantiated by winter ship track measurements in Cook Inlet, Alaska. Information available in open literature relates to performance of special purpose icebreakers, which points to a need for facts regarding performance of conventional ships in ice.

1. INTRODUCTION

The most widely used guidelines for design of excavated coastal ship channels exist in two references: USACE (1983) and PIANC (1997). The US Army Corps of Engineers has recently revised the material of USACE (1983) to be published as a chapter in the "Coastal Engineering Manual" (USACE in preparation). This later Corps guidance, which is generally compatible with PIANC (1997), mentions practical ice navigation problems and suggests subjective channel design allowances. Neither set of guidelines objectively addresses ice in channels or cold region conditions as they affect ship maneuverability and safety of navigation. This paper supplements present channel design guidance.

2. PRACTICAL CONSIDERATIONS FOR ICE AND WINTER CONDITIONS

Winter conditions along northern seacoasts, estuaries, lakes, and rivers cause ice to be an occasional, if not chronic, concern for safe and efficient navigation. About 42 percent of the Earth's surface experiences temperatures below 0°C during the coldest month of any year. Longer nights and increased low visibility accompany the presence of ice. Shipboard mechanical equipment, instruments, and communications apparatus are less efficient and more prone to failure in cold temperatures. Aids to navigation become less effective, and maneuvering in ice is much more difficult.

A designer of an excavated channel must consider the following aspects of ice navigation:

a. Ship speed and maneuverability are retarded,
b. Ice impact forces can divert vessels from their intended course,
c. Darkness is more common,
d. Low visibility conditions (fog and precipitation) are more common,
e. Winds can be at their worst,
f. Visual aids to navigation are less effective,
g. Shipboard instruments are more prone to malfunction from cold, icing of external sensors, and ice-related hull and power system vibrations,
h. Frazil ice can clog seawater intakes, raising the risk of overheating engines,

i. Repeated passages through icy channels increases local incidence of brash ice (small broken pieces) and exposes water surface to cold air, accelerating new ice growth,
j. Assistance or rescue by tugs is more difficult, and
k. Crews are more strained and fatigued in the face of these challenges.

The policies and practice of pilot associations, shipping companies or vessel insurance underwriters may call for additional keel and bank clearances beyond those allowed in temperate ice-free conditions. The Coast Guard or other regulatory agencies may also impose special ice rules. These marine interests should be solicited for their views early in the project.

3. ELEMENTS OF CHANNEL DESIGN

Site-specific considerations of hydrodynamic conditions, characteristics of ships, and channel stability are combined to derive cost-effective channel geometry defined by excavated depth, width, length, and alignment. The optimum excavated channel bottom elevation is a function of factors illustrated in Figure 1. Depth factors are generally mitigated by ice and winter conditions. Estuarine waters are generally saltier in winter and therefore more buoyant. Ice damps wave action. Ships that reduce speed in ice also reduce their squat.

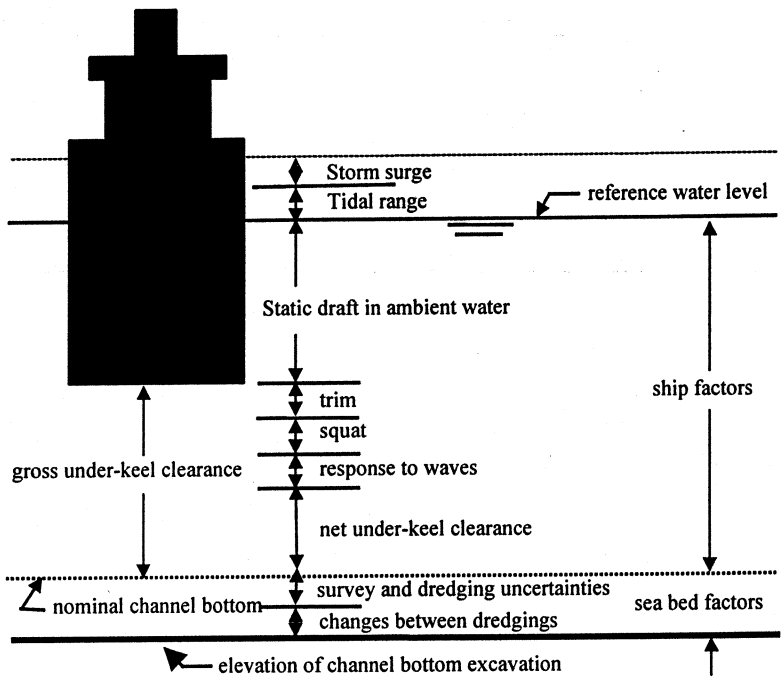

Figure 1. Typical elements of channel depth design.

Figure 2 illustrates the basic elements of one-way channel width design. A two-way channel has two sweep paths separated by a central passing clearance. The normal sweep path includes variability of a selected ship's course in a temperate environment, as presently recommended by PIANC (1997) or USACE (in preparation). Extreme sweep path allowances concern ice effects.

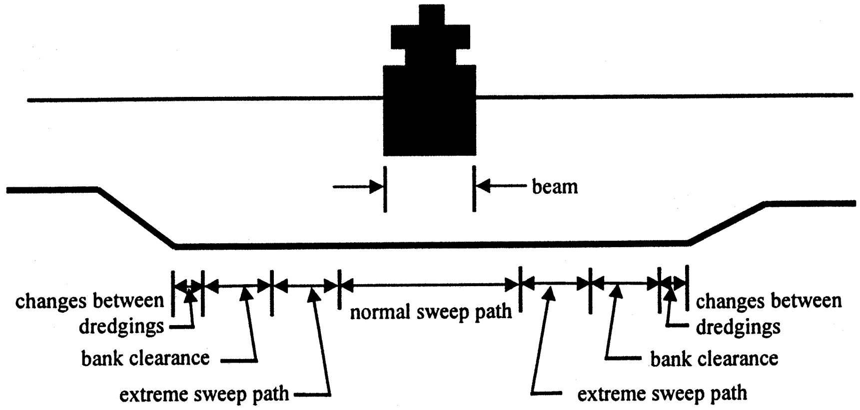

Figure 2. Typical elements of channel width design.

4. ICE EFFECTS ON SHIP MANEUVERS

Nomenclature defining sea ice conditions is specified by the World Meteorological Organization (WMO 1970). Broken ice, versus continuously formed level ice, may be concentrated less than 10 tenths (100 percent coverage) or it may have been broken by wind, currents, or previous passages and subsequently reconsolidated. Broken ice, by this definition, corresponds to the ice condition usually encountered by conventional ships in sub-arctic waters.

Ice effects on ships include increased resistance, increased structural stress, retarded maneuverability, and reduced efficiency of ships' mechanical and electrical systems. Ice conditions of concern include ice concentration (coverage), thickness, pressure, and shear zone conditions (CCG 1992). Retarded maneuverability, *e.g.,* slow response to helm orders and increased turning radius, broadens the prospective sweep path of a vessel in an excavated channel. Maneuverability reductions and resistance are generally proportional to ice thickness and pressure. Snow-cover and agglomerated brash ice increase resistance forces. Repeated vessel transits can exacerbate agglomerations of brash ice in confined channels, since newly opened water freezes to increase the total ice volume (Ettema 1991). Pressure (compression by wind or hydrodynamic forces) and ridged and rubble conditions at the shear zone, *i.e.,* the boundary of shore-fast ice, also compound navigation difficulties.

Hull features associated with relative ice response are length-to-breadth ratio, flare, mid-body length and shape, and bow and stern shape. The draft Polar Code (IMO 1997) does not deal directly with ship maneuverability in icy channels, but it does promote many specialized ship features, operations, and crew capabilities for polar navigation. Few of these features are found on ships arriving in icy waterways from more temperate ports of the world.

Long, parallel mid-bodies typical of modern bulk carriers and containerships restrict maneuverability in high ice concentrations and maximize frictional resistance from ice contact. Conventional low flare angles give high lateral forces when impacting floes asymmetrically. Conventional ships' bows have a tendency to bounce off larger and stronger ice floes with subsequent diversions of course along oblique leads. Slow response to helm orders and an extended turning diameter in ice broaden the sweep of corrective maneuvers. Pilots of the Southwest Alaska Pilots Association report this as a common winter circumstance in navigating upper Cook Inlet, Alaska (Alaska District 1996). Pilots of ships in winter on the Gulf of St. Lawrence and Baltic Sea also encounter this condition (Keinonen et al 1991). Great Lakes ore-carriers are notoriously difficult to maneuver in ice, even with icebreaker escort (Captain Lawson Brigham, US Coast Guard, ret., personal communication).

Icebreakers have extraordinary hull shapes, power, and steering mechanisms. Conventional ships, even with ice-strengthened hulls and extra power, will typically exhibit stronger responses to ice forces. Keinonen et al (1991) reviewed maneuverability of non-nuclear icebreakers in service. In general, a sharp reduction in overall ship maneuverability occurs at ice concentrations above 8 tenths (80 percent), in comparison to open-water performance. Masters of ships serving in the Gulf of St. Lawrence and Baltic noted that convergent wind and associated ice pressure further degrades ship maneuverability. Pressurized ice in Arctic waters has stopped some of the world's most powerful icebreakers.

Quantification of ship performance in broken ice is difficult due to variability of conditions. Random magnitudes and directions of ice forces on ships stem from both impacts and frictional resistance. Impacts of wind- or current-driven ice forces can be oblique to the course of the ship, causing a sudden diversion. Continued oblique impacts and frictional resistance retard response to such a diversion.

Broken glacier ice, in the form of icebergs, bergy bits, or growlers, is more irregular, both in shape and distribution on the water. Glacier ice is harder than frozen seawater and may contain gravel and rocks, which can reduce its buoyancy, freeboard, and visibility. Bergy bits and growlers such as this are common in parts of Prince William Sound, Alaska. Impacts with glacier ice are generally more dangerous than equivalent impacts with sea ice.

Reliability in winter conditions of navigation systems to align the ship in the channel is a concern. Hull and machinery vibrations from ice contact, without special mounts and constant attention, can suddenly render electronic positioning systems inoperable. Winter conditions, *e.g.,* cold temperatures, snow, freezing rain, and rime ice, can render external antennae inoperable. Hull-mounted acoustic fathometers are often inoperable due vibrations and increase turbulence by the transducer. Combinations of these difficulties will sometimes place the ship at the boundary of or beyond its normal sweep path in a channel.

5. CASE STUDY: KNIK ARM SHOAL CHANNEL, ANCHORAGE, ALASKA

Knik Arm Shoal is a stable glacial deposit located along the shipping route 6 miles southwest of the Port of Anchorage in south central Alaska at latitude 61° 12' N. The shoal's 8.5-m depth at Mean Lower Low Water causes tide-associated delays to deep-draft vessels serving the port. Spring tidal ranges at the site exceed 10 m and tidal currents regularly exceed 4 knots.

The US Army Corps of Engineers addressed the feasibility of an excavated channel across the shoal in a series of studies (USACE 1996). The final channel width of 310-m includes large safety factors to accommodate winter conditions and changing bottom conditions in upper Cook Inlet. A normal (but still unusually wide) sweep path of 3 design vessel beams was enclosed by two extreme sweep path allowances of 0.75 beams each. Additional safety clearance and shoaling-between-dredgings allowances comprise the total 310-m proposed bottom width. Excavation is scheduled for the ice-free season of 1999.

Tracks of Knik Arm Shoal crossings by two commercial liner ships were measured from 23 December 1996 to 27 April 1997 to assess the adequacy of the width of a channel authorized for excavation (Terra Surveys 1997). Figure 3 illustrates the variability of winter ship tracks measured across the proposed excavation, which lies in the center of the contoured area. The channel centerline is nearly identical to the course routinely followed by pilots of deep draft ships approaching or departing Anchorage prior to excavation.

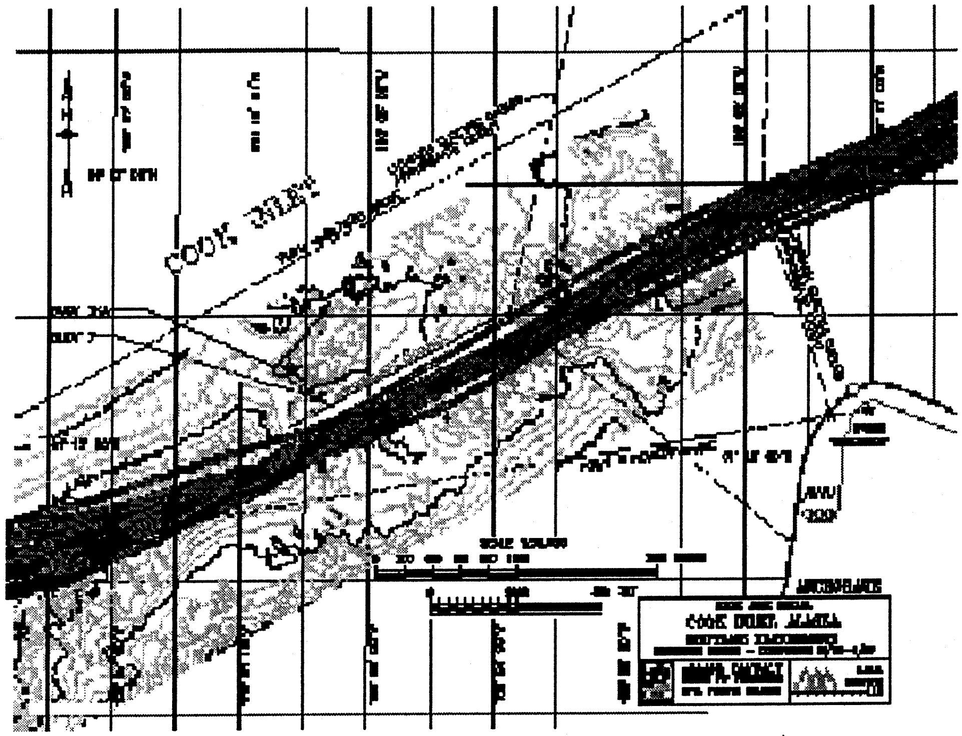

Figure 3. Measured ship tracks superimposed on chart of Knik Arm Shoal, Cook Inlet, Alaska.

Navigation conditions on Knik Arm of upper Cook Inlet, Alaska, during ship track measurements were compared to navigation conditions in previous winters. The winter began with unusually cold conditions during October, November, and December 1996, but ended with unusually mild conditions from January to April 1997. Ice was encountered by ships early in the season, but did not build to concentration or thickness that represent the worst historical constraint on navigation. Table 1 presents compares ice reports during selected ship track measurements with previous winters and climatological averages. Corresponding level ice thickness was in the range of 0.5 to 1.0 m, but Cook Inlet ice is prone to ridging and floes of harder sediment-laden beach ice are intermixed with sea ice. Floating beach ice thickness can exceed 2 m.

The 1.5 beam width added to the channel design for winter conditions increased excavation cost by about 25 percent. This addition was justified by the variability of ship tracks measured. The recommendation was reviewed with intense scrutiny, but was unanimously supported by pilots, ship owners, and regional maritime interests. The wider channel was ultimately authorized for construction.

6. EXAMPLE COMPUTATION

Keinonen et al (1991) found that non-nuclear ice-breakers, whose length-to-beam ratios ranged from 3 to 5, could achieve turning diameters from 5 to 25 times their length in level ice. Conventional ships with longer length-to-beam ratios, less rounded shapes, and less power can be expected to achieve turning diameters in the upper end of this range or beyond. A ship near the boundary of its normal sweep path diverted by ice outside this path will correct from a sudden diversion in a manner similar to that shown in Figure 4. The ship's centerline offset from the normal sweep path, plus half the beam, equates to an extreme sweep path, as indicated in Figure 2.

Table 1. Comparison of Ice Conditions at Knik Arm Shoal, Cook Inlet, Alaska, Reported by the US National Weather Service with Average Seasonal Conditions (LaBelle et al 1983.)

NWS Reports 1994 – 1995		NWS Reports 1995 – 1996		NWS Reports 1996 – 1997		Marine Ice Atlas (LaBelle et al 1983)	
Date	**Report**	**Date**	**Report**	**Date**	**Report**	**Period**	**Average**
12/26	N/YNG Brash	12/27	5-7 YNG/N	12/23	5-7 YNG/FL	12/16-31	4-6 YNG/N
1/11	7-8 YNG/N/FL Brash	1/10	2-4 N/YNG	1/6	9-10 YNG/FL	1/1-15	7-9 FL
1/25	8-10 YNG/N/FL	1/24	9-10 YNG/FL	1/20	0-2 YNF/FL Brash	1/16-31	7-9 YNG
2/8	Open	2/7	5-7 YNG/FL	2/12	5-7 FL/YNG Brash	2/1-15	7-9 N/YNG
2/20	4-6 YNG/N	2/21	5-6 FL/YNG	2/24	Open	2/16-28	7-9 N/YNG
3/8	3-5 YNG/N	3/6	Open	3/3	1-3 FL/N Brash, Strips	3/1-15	7-9 N/YNG
3/27	5-7 YNG/N	3/20	Open	3/17	6-8 N/FL/YNG Strips	3/16-31	1-3 N/YNG

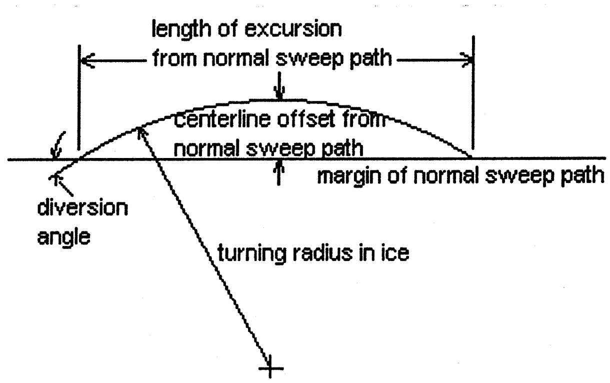

Figure 4. Geometry related to extreme sweep path in ice.

A 240-m-long, 32-m-wide containership (length-to-beam ratio 7.5), the design ship for Knik Arm Shoal channel, might achieve a turning radius in ice of 3,000 m. An initial course departure angle of 5 degrees would cause an 11.5-m centerline offset. Course corrections and turning radii on this order were exhibited in measured ship tracks in 6 to 8 tenths concentration (Terra Surveys 1997). A channel width beyond the normal sweep path of 1.0 beam (32 m) should be allowed for this circumstance. The associated length of excursion from the normal sweep path would be over 262 m.

6. CONCLUSIONS AND RECOMMENDATIONS

Many scenarios of combined forces and extreme circumstances are conceivable at points along a shipping route. An analysis as above is recommended for channels in icy waters, with a view toward ship performance in ice, local ice conditions, and other winter conditions. A diversion angle of 5 degrees and turning diameter of 25 times the design vessel length is recommended for initial assessments. Designers should subsequently consider physical and numerical modeling and ship tracking as tools to optimize channel width. The cost of excavation may be as much as 40% more than a corresponding temperate climate design, therefore a rigorous investigation is warranted. The cost of an accidental grounding and cargo spill in winter is likely to be much more. Further applied research is needed, focused on maneuverability of conventional ships in broken, ridged, and pressurized sub-arctic ice.

7. REFERENCES

CCG 1992. "Ice Navigation in Canadian Waters," Canadian Coast Guard, Ottawa

Ettema, R. 1991. "Ice Formation in Navigation Channels," Bulletin 74, Permanent International Association of Navigation Congresses, Brussels

IMO 1997. "The (Draft) International Code of Safety for Ships in Polar Waters (Polar Code)", Sub-Committee on Ship Design and Equipment, International Maritime Organization, London

Keinonen, A., Browne, R., and Revill, C., 1991. "Icebreaker Design Synthesis: Analysis of Contemporary Icebreaker Performance," AKAC, Inc., for Transport Canada, Ottawa

LaBelle, J., Wise, J., Voelker, R., Schulze, R., and Wohl, G., 1983. "Alaska Marine Ice Atlas," University of Alaska Anchorage, Environmental and Natural Resources Institute, Anchorage, prepared for the US Dept. of Transportation and the US Dept. of Energy

PIANC 1997. "Approach Channels, A Guide for Design," Supplement to Bulletin No. 95, Permanent International Association of Navigation Congresses, Brussels

Terra Surveys 1997. "Ship Track Measurement and Analysis, Knik Arm Shoal and Vicinity," contract report for the US Army Corps of Engineers, Anchorage

USACE 1983. "Hydraulic Design Guidance for Deep-Draft Navigation Projects," EM 1110-2-1613, US Army Corps of Engineers, Washington, DC

USACE 1996. "Deep Draft Navigation Interim Feasibility Report and Environmental Assessment, Cook Inlet, Alaska," US Army Corps of Engineers, Anchorage

USACE (in preparation). "Navigation Projects," Coastal Engineering Manual, Ch. V-5, US Army Corps of Engineers, Washington, DC

WMO 1970. "WMO Sea-ice Nomenclature", WMO/OMM/BMO-No.259.TP.145, as amended, World Meteorological Organization, Geneva